THERMOSTATS

AND TEMPERATURE-REGULATING INSTRUMENTS

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TO MY BROTHER
EZER GRIFFITHS, O B E, D Sc, F R S
As a token of admiration and gratitude

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PREFACE

Since the publication of the last edition of this book further progress has been made in the analysis of control systems. Systems have been developed to minimize deviation from the required temperature and to ensure rapid correction should such deviation occur. Servo-systems have been applied. The use of electronic mechanisms in temperature-control instruments is rapidly increasing and proving of great value.

Some references are made in this edition to these new features and it is hoped the book will give the reader some indication of the progress which has been made. It may be emphasized here that an instrument cannot of itself be expected to provide the solution to a problem of temperature-control, but is merely a scientific tool employed to help solve the problem.

Theories of temperature control are not as yet sufficiently comprehensive for a final discussion to be given. Some of the more important views put forward have been included in the Appendix; the reader who wishes to pursue the subject further is recommended to consult the original papers, which are listed at the end of the Appendix.

References to the literature of the various types of regulators are given at the end of each chapter.

R. G.

SWANSEA,
June, 1950.

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CHAPTER 1

Introductory

THE maintenance of a constant temperature-value is a necessity in many technical processes and laboratory experiments. The temperature to be controlled and the closeness of control will vary widely in different circumstances ; in all cases, however, the basis of control is the same. Random disturbances affect the temperature, and it is necessary to employ some form of thermostat if the temperature is to be maintained at a constant value. Three main components have to be considered in connection with the thermostat.

It is necessary, in the first place, to measure or ascertain the value of the temperature by means of a pyrometer or temperature-sensitive element ; very frequently too much is expected of the pyrometer. It must not be forgotten that " contact" pyrometers measure the temperature in the immediate vicinity of their hot tip or bulb, and not the general temperature of the oven or furnace, although they are sometimes affected by their surroundings as a result of radiation. In a well-insulated space, such as can be arranged under laboratory conditions, this variation of temperature should of course be extremely small, or negligible, but in industrial furnaces there may sometimes be large temperature-gradients. It is essential, therefore, that the pyrometer or *sensitive element* be placed in the correct position, so that the temperature measured is the true one, or at least bears a constant, known relation to the true value. Various forms of sensitive element are used for automatic temperature regulation, and these are dealt with in the text.

The second component that has to be considered is what may be termed the *control gear.* This component reacts to the changes taking place in the sensitive element and alters the amount of heat liberated by the third component, situated in or around the controlled space ; this last component may be termed the *heating element.*

The correct relationship between these three components is the basis of successful temperature-control.

When there is a change of temperature in the controlled space, a certain time must elapse before the sensitive element, which records this change, acquires the new temperature. When this occurs, the control gear is set in operation to regulate the amount of heat liberated by the third component. The regulator is not able to stop this operation as soon as enough adjustment has been made, because of the time-lag. The shorter the time required for the

space to return to the normal value compared with the time-lag, the further will the temperature overshoot before the regulator responds to the condition when the space has reached the normal temperature value There is a danger of setting up an oscillation of increasing amplitude if the rate of return to normal value is too rapid Complete elimination of fluctuations of temperature would, of course, dispense with the need for the appropriate controlling actions

Three factors influence the rate at which the regulator changes temperature (*a*) the temperature of its surroundings, (*b*) its own temperature, and (*c*) the "setting" of the control mechanism

The operation of the control mechanism might be arranged to depend either on the amount by which the temperature departs from the controlled value, or on the rate of change of temperature Possibly the second differential of the temperature with respect to time might be used, or an integral, or some function of these Again, these latter might be used to decide the setting of the control mechanism or the rate of change of setting etc There are many complex possibilities

Let us now assume a simple case where the thermostat operates, as explained in Chapter 3, by the movement of a column of mercury as the result of temperature-changes The make and break of the circuit occurs between the mercury and a wire placed near its surface Make and break seldom occur at the same level, due to various causes such as contamination of the mercury surface, surface tension, and other effects There is a 'backlash', and "hunting" of the temperature over the range of the backlash is unavoidable An alternative method of control is to make the action continuous by arranging for the resistance to change continuously with the level of mercury instead of from infinity to zero, as in the make and-break system A similar continuous action takes place in a form of thermostat frequently used for controlling gas-supply (p 16)

Considering next the heating element in relation to the other components as the heating element has a certain heat-capacity, it will require time to cool down or heat up from a particular temperature In the meantime (as we have seen) the temperature of the space will have continued to rise or fall, and with it the temperature of the sensitive element

The resultant effect of all these actions is a swing from side to side of the required controlled temperature Time-lags of several minutes may occur, particularly under industrial conditions This "hunting" or periodic fluctuation of the temperature due to the heater, etc, may be minimized by improving the thermal contact between the heater and the sensitive element In practice this is usually done (when the construction allows) by vigorous circulation or agitation of the medium in which the two components are placed A further step has been taken in one type of thermostat (p 48) by placing

a part of the sensitive element very close to the heater, and in a direct stream of air from it. The tendency in this design is to control the mean temperature of the heater. The final step is to identify the heating and sensitive elements by using the one for both purposes. As will be shown later in the discussion on the theoretical aspects of temperature-control, this method in certain circumstances is not always advantageous.

Industrial controllers

In industrial controllers apart from the sensitive element, the control mechanism and the heating element or controlled device, e.g. a valve, there is the important part of the system to be considered—the process itself.

Consequent upon variation in the controlled device the process is restored to balance. This system is termed a "closed-loop" control, the process completing the loop between the controlled member and the measuring element.

Instrumental developments are far ahead of their application and the controlled process, despite its importance, is the link about which least is known. Mathematically the behaviour of the other components of the loop can be predicted with some certainty, yet it is only in the simplest of processes that a fairly accurate estimate of the likely control conditions can be made when the plant is being designed. Unexpected process lags, surges and other upsets occur which may require repositioning of the sensitive or measuring element, or altering the design of a condenser or heat interchanger, etc.

At present, therefore, the approach to the problem of design is an empirical one, and the aim should be to replace it by one more fundamental, which would allow the requisites of the control system to be accurately predicted in the design stage.

Classification of control instruments

A logical classification is somewhat difficult, but broadly an attempt has been made in this book to classify the various types into groups, according to the form of sensitive element, with certain chapters devoted to particular fields of application such as room control, etc.

CHAPTER 2

Thermostats based on the expansion of gases with temperature

Gases have the largest coefficient of expansion of known substances, and there is relatively little difference in the magnitude of the coefficient for different gases

When one of the permanent gases is used as the expanding medium in a thermostat, the temperature-range over which the instrument is applicable is limited only by the strength and porosity of the envelope at high temperatures The number of forms of thermostats of this class is comparatively small, partly because high sensitivity can be obtained only with difficulty, and partly because the instrument has to be of the "sealed in' type to avoid the effect of changes of barometric pressure on the volume of the gas in the thermostat bulb

The simplest form of this type of thermostat consists of a vessel containing the expansible gas, which is inserted into the space to be controlled The change of volume of the gas with change of temperature causes movement in a column of mercury, thus making or breaking—either directly or through the medium of relays—an electric circuit controlling the heating of the space The vessel which contains the gas should have as large a surface area as possible, and have sufficient volume to reduce to negligible amounts the effect of room temperature variations on the capillary and contact tube volumes The range of temperature values which can be controlled with this type of instrument is great, but the sensitiveness is not high nor easily increased Fig 1 shows diagrammatically a form of regulator of this type[1] A bulb E is filled with hydrogen and communicates with a mercury column contained in a barometer tube The bulb is usually placed in the heated space, and the barometer tube outside Into the walls of the tube are sealed two platinum wires A and B, serving to lead the current into and out of the mercury respectively, the mercury is in series with the electrical heating circuit The circuit breaks at the junction of hydrogen and mercury at A The mercury does not tarnish, since no compound of hydrogen and mercury forms on sparking A point of advantage with this form of thermostat is that regulation of temperature is independent of variations of atmospheric pressure because the gas is completely enclosed The regulator is not free, however, from errors due to variations in room temperature unless precautions are taken to select suitable capacities for the bulb and connecting-tube, and to ensure the correct volume of mercury

below and above the level of the platinum contact. Nevertheless these errors are not large.

The height of the mercury in the contact tube at A, and consequently the temperature at which make and break occur, are regulated by means of the lower stopcock. The tube is furnished with two small bulbs C and D. The mean pressure in the large bulb E is so chosen that the mercury in the top bulb D occupies about half the volume of this bulb. It is convenient to make the pressure of the gas in E about equal to mean atmospheric pressure; the

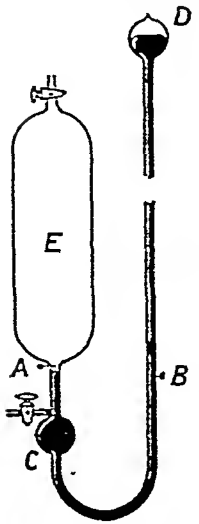

Fig. 1.—Gas-expansion thermostat

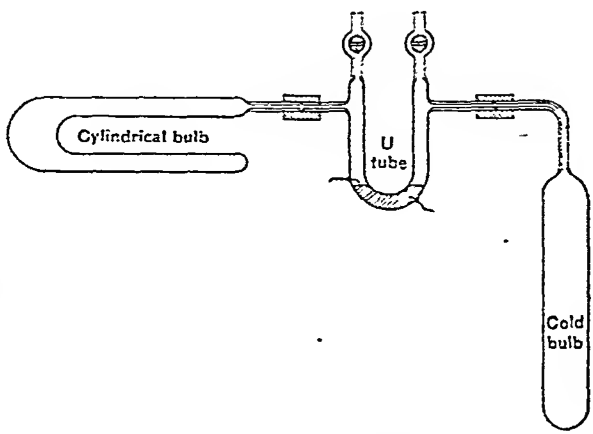

Fig. 2.—Principle of the Haughton-Hanson thermostat (original design)

length of the vertical tube is then that of an ordinary barometer tube, so that possible leakage of hydrogen through defective taps is minimized. The lower small bulb C would supply sufficient mercury to fill the upper small bulb D in the event of overheating, without allowing the lower level of the mercury to be depressed to the bottom of the tube; if this happened, bubbles of gas from E would pass over and destroy the vacuum in the upper bulb D.

Haughton-Hanson thermostat

An instrument of this class which is fairly extensively used in laboratory work is the Haughton-Hanson [2] type of thermostat (Fig. 2). In principle this thermostat consists of a double-walled silica vessel (known as the "hot" bulb), which is well lagged thermally and wound on the outside with resistance wire for heating purposes. The air space between the two walls

is connected by capillary tubing to a U tube containing mercury in which suitable electrical contacts are sealed The other side of the U tube is connected to another bulb, referred to as the "cold" bulb This latter bulb is kept at a constant temperature, and serves to eliminate the effect of variations of atmospheric pressure on the system since it makes the system totally enclosed Fluctuations of temperature in the "hot" bulb cause changes in the air pressure in it, resulting in displacement of the mercury in the U tube An electrical circuit is completed or broken, which has in it a relay controlling the current flowing in the furnace winding Since this thermostat was introduced details of the apparatus have been modified and alternative designs suggested for some of the parts The more important of these will now be considered

Modified U tube—The form of control tube at present used is shown in Fig 3 The tube A is connected to the "hot" bulb and B to the "cold" bulb C is connected to a slow heating and cooling device to be described later The ends of the tubes D and F are connected by rubber tubes to thistle funnels, with the aid of which mercury can be let into the U tube and into D The latter adjustment[3] enables the controlled temperature of the thermostat to be altered to a small extent by means of small changes in the air pressure in the hot bulb Admitting mercury into D raises the pressure in the bulb and causes the temperature to fall slightly Removing the mercury has the reverse effect It is advisable to give the furnace some time preferably about 24 hours if heated from the cold, to allow steady conditions to be attained before making final temperature adjustments

On cooling the thermostat from high temperatures to, say room temperature mercury in the U tube tends to be sucked back into the "hot" bulb unless precautions are taken It is obvious of course, that in heating to and cooling from the control temperature, the bulb should be put into communication with the atmosphere by suitable manipulation of the taps, but in the event of inadvertent wide fluctuations of temperature of this order, sucking back is liable to occur If the limb of the U tube is more than large enough to take the whole volume of mercury, then the air can find its way past the mercury column, this, however is not a complete safeguard against sucking back, and it is advisable to provide a trap, which may take the form of a porous diaphragm interposed in the tube, or a means of obtaining a complete change in direction of the air stream as illustrated at E in Fig 3 These traps are not, however, completely satisfactory, and the safest procedure is to remove the mercury from the U tube (by opening the tap at F after lowering the thistle funnel connected to it) before opening any part of the apparatus to the atmosphere

A further point to be guarded against is that the U tube should not be subjected to possible heating by direct sunlight for this may heat one limb first and then the other during movement of the sun

Contamination of the mercury due to sparking at the contact surface can be a troublesome feature, causing erratic working of the thermostat. The sparking can be minimized by introducing a condenser in parallel with the contacts, or better still a Westinghouse rectifier across them ; but the effective remedy is to decrease the current that has to be broken at the contacts by the use of a thermionic valve or similar relay, as described later (see p. 123).

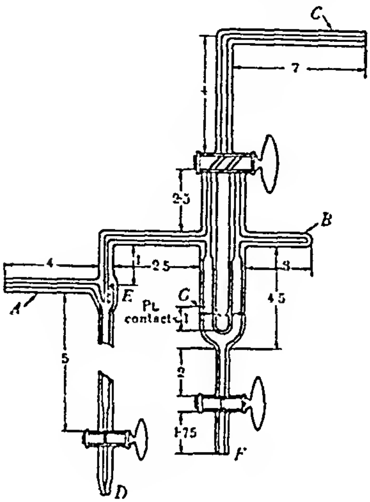

Fig. 3.—Control tube for modified Haughton-Hanson thermostat (All dimensions in centimetres)

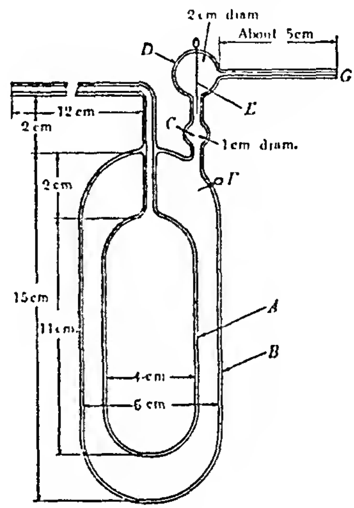

Fig. 4.—" Cold " bulb in modified Haughton-Hanson thermostat

Re-designed forms of " cold " bulb.—As previously stated, the temperature of the " cold " bulb should be kept at a constant value. For short periods of time, this can be done most effectively and efficiently by immersing the bulb in melting ice contained in a Thermos flask. When, however, the furnace is to be used for longer periods than that during which the ice will remain unmelted in the flask, it is necessary to use other methods. One of these methods is to enclose the bulb in a liquid the temperature of which is controlled. In one form the inner glass bulb *A* (Fig. 4) is connected to the U-tube, and the annular space between it and the outer bulb *B* is filled with mercury. The mercury just rises into the small bulb *C* when the apparatus is at the lowest temperature it is likely to reach when not in use. The space above this is filled with hydrogen. The bulb *D* enables the mercury to rise in the tube connecting *C* and *D*, without an excessive accompanying rise in pressure in the hydrogen atmosphere. A platinum wire *E* reaches into the tube joining *C* and *D* and makes contact with the mercury. A second platinum wire *F* makes contact

with the mercury in the bulb The tube G is used for filling the apparatus and is then drawn off so as to leave it about 2 cm long

The outer bulb B carries a heating winding over the lower two thirds of its length the resistance of the winding being about 50 ohms for 110 volt supply This is in series with a 500-ohm resistance When the mercury makes contact with the upper platinum wire the heating coil is shunted by a 45-ohm resistance and the current of the heating coil decreased A condenser of about 0 1 μF capacity across the contacts helps to reduce sparking There is a small fluctuation of the order of 0 1° C in the temperature of the bulb For the highest accuracy it is advisable[4] to lag the tube connecting the bulb with the platinum contact

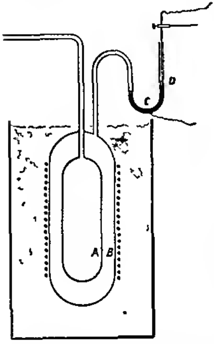

Fig 5 —Device for maintaining temperature of cold bulb constant and fine adjustment of temperature setting

A similar device for cold bulb temperature control has been suggested[5] in which the mercury is replaced by toluene (Both liquids have their advantages e g mercury has the greater thermal conductivity while toluene has the higher coefficient of expansion) In this device (Fig 5) a U tube C containing mercury communicates with the bulb B Expansion and contraction of the toluene with change of temperature makes and breaks the circuit at the contact D which controls the heating current passing through the coil surrounding the outer vessel B When contact is made the heating current is decreased due to a part of the heater winding being shorted

Accurate setting of the temperature to be regulated can be made by adjusting the position of the contact D This device can be used to alter rapidly and accurately the temperature of regulation of the thermostat furnace from one setting to another The effect on the temperature of the furnace of known movements of the contact can be determined experimentally at various temperatures and the values obtained used for adjustment purposes Rapid changes to lower temperatures can then be made by allowing the furnace to cool down with both taps on the main control U tube open until the temperature falls to within a few degrees of the required figure , allowing

the furnace to settle down ; and then adjusting the contact by the required amount.

In one particular apparatus a movement of 1 cm of the platinum contact altered the temperature of the thermostat approximately 1°C, and with this arrangement it was possible to adjust the temperature over a range of 50° C with an accuracy of 0·1° C.

When the thermostat is allowed to cool down to room temperature after use, it is necessary to prevent air sucking back into the bulb *B*. This is done by allowing the furnace to warm up until nearly all the mercury is in the open limb of the U-tube. The greater part of the mercury is then removed by means of a dropping-tube. Toluene is added until the open limb is almost full. The tube of a siphon connected to a reservoir of toluene is then inserted into the limb of the U-tube and the toluene allowed to be sucked over.

This is a somewhat troublesome operation, and a further slight drawback in the use of this particular cold-bulb device is that it requires a supplementary source of current at low voltage and a relay to operate it.

Yet another form [6] of " cold " bulb is that in which the device acts not merely in this capacity but also replaces the U-tube, and safeguards the apparatus against sucking-back of the mercury in case the furnace is accidentally cut off. The capillary tube from the " hot " bulb is connected to the open limb of a mercury barometer, into which the contacts are sealed. As mentioned in connection with the simple form of gas-expansion thermostat, by using suitable capacities in the " hot " bulb and the connecting-tube, and the correct volume of mercury below and above the level of the platinum contact, it is possible to cause the errors due to changes in room temperature to cancel each other. To avoid mercury being sucked back from the barometer tube into the " hot " bulb when the furnace is allowed to cool, the tubing joining the " hot " bulb to the barometer is carried to such a height that if the whole system were evacuated the mercury would not reach to the top of the tube.

This form of " cold " bulb is very accurate, but it suffers from the disadvantages of having a long, fragile barometer tube, and the necessity of knowing the coefficient of expansion of the glass and also the volumes of the tubes, etc. The data need, however, only be known to within a few per cent.

Auxiliary furnace.—The Haughton-Hanson type thermostat functions by keeping the mean voltage at a definite value, which is such that the heat input due to the current produced in the furnace by that voltage is just sufficient to compensate for radiation and other heat losses. If we have a second main furnace which will be affected by changes in room temperature to the same extent as the thermostat furnace, and connect it in parallel with the terminals of the thermostat furnace but in series with the relay, resistances, etc. the temperature of the second furnace will be regulated at the same time as that

of the first Theoretically, there is no limit to the number of furnaces which can be run in this way The mean temperature of the main large furnace over very long periods of time is independent of variations of room temperature Over short periods, however, some variation of temperature may occur If, for instance, the temperature of the room should rise, the equilibrium of the subsidiary small thermostat furnace would be affected in a comparatively short time, during which the temperature of the main furnace would be sensibly unaltered, owing to its greater size As a result, however, the power input in both furnaces would be reduced by the action of the thermostat, and the temperature of the large furnace would drop in a short time, until the power was applied to the inner portion of the furnace close to the point at which the temperature was measured Much later, of course, the large furnace would tend to regain the original temperature

Where the highest possible accuracy is desired, the thermostat furnace itself should be used but the second furnace can be used where a variation of 2° C is unimportant An advantage of using a second furnace is that the tube of such a furnace is cheaper and easier to replace than the special silica bulb of the thermostat furnace

Slow-cooling and heating

In conjunction with the Haughton Hanson thermostat, slow-cooling or heating devices can be used to regulate the rate of cooling or heating of the thermostat furnace It may be stated at the outset that these devices cannot be used with the barometer tube type of "cold" bulb

In the original design, a bulb is connected to the U tube by capillary tubing so that either limb of the U tube may by turning the two-way tap on that tube be put into communication with the bulb When it is desired to cool the furnace slowly, the whole bulb is immersed in hot water or oil contained in a vacuum flask As the temperature of the air in the slow cooling bulb falls, air is extracted from the limb of the U-tube away for the furnace This reduces the pressure on the gas in the hot furnace bulb, and the expansion which otherwise would take place is, owing to the breaking of the circuit, automatically balanced by a fall in temperature of the furnace For slow-heating the bulb is connected to the other limb of the U tube

This method of slow cooling or heating is suitable for rates of change of temperature greater than 20° C per hour over a comparatively short time, the rate of cooling being controlled by the size of the bulb, the temperature of the liquid, or the lagging of the vessel

Another ingenious method of slow-cooling consists in connecting the two sides of the U tube together by means of a very slow leak The amount of mercury is adjusted so that when the platinum contact point at *G* (Fig 3) is just making contact, the mercury in the other limb is at a higher level To

maintain this difference in level, a definite pressure on the furnace side of the U-tube is necessary. The leak tends to reduce the pressure and, therefore, the furnace has to heat up in order to prevent this reduction of pressure, doing so automatically because the heating circuit is completed as the mercury rises to make contact with *G* on lowering of the pressure. Conversely, if the mercury level in the limb on the furnace side is higher than in the other, the action of the leak is such that the furnace has to cool to keep the mercury in the neighbourhood of *G*. The rate of heating or cooling can be controlled by altering the head of mercury, or altering the value of the leak. The chief obstacle preventing extensive use of this device is the difficulty of obtaining suitable leak tubes which are not fragile.

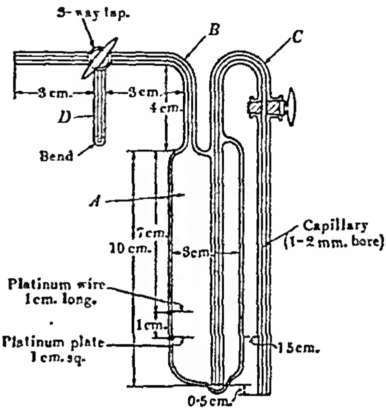

Fig. 6.—Electrolytic cell for slow-cooling (N.P.L.)

Use of electrolytic cell.—The arrangement for slow-heating or cooling now used at the National Physical Laboratory makes use of an electrolytic cell.[7]

The bulb *A* (Fig. 6) is filled with a saturated solution of chromic acid in equal parts of water and sulphuric acid. One electrode is in the form of a platinum plate 1 cm square, and the other a platinum wire to form the anode. The use of a plate instead of a wire for the cathode enables higher currents to be used before hydrogen is evolved. In the cell illustrated, a current of about 8 milliamperes can be used without excessive evolution of hydrogen. The oxygen evolved is passed by the tube *B* to one or other side of the U-tube of the thermostat. If it passes into the cold-bulb side of the U-tube, the rise in pressure will have to be balanced by a rise in temperature on the furnace side, and consequently the furnace heats up. Alternatively, if the gas is passed into the hot-bulb side, this will have to cool in order to maintain constant pressure. The rate of heating or cooling is governed by the quantity of gas evolved, which depends on the current passing through the electrolytic cell. The cell can be run off the D.C. mains with a potential-divider to control the current. The resistance of the cell varies with the amount of gas clinging to the electrodes, etc., and the behaviour of the cell is greatly improved if a ballast resistance of 500-ohms or more is introduced in series with the plate. This has also the effect of enabling finer control of the current to be obtained.

The tube *C* (Fig. 6) is used for filling and emptying the apparatus. If the

tube cell is designed with a tap at the bottom, difficulty is experienced with the tap either leaking or sticking due to the chromic acid attacking the lubricant

With this cell arrangement it is possible to obtain rates of heating and cooling up to 20° C per hour at a temperature of about 600° C

When slow heating is being carried out, the pressure on both sides of the U tube rises steadily, and it is advisable to open the whole apparatus to the atmosphere every 200° or 300°, so as to prevent the pressure from becoming excessive With slow-cooling on the other hand this is unnecessary, as the pressure remains constant

General notes on the thermostat

Required values of resistances—It was originally considered necessary to have a number of resistances to control the current, in order to enable the maximum and minimum currents to lie fairly closely to the mean current which would keep the thermostat at the required temperature It has been found by experience that this is unnecessary and that two values of maximum current (either full on or with a small resistance in the circuit) and two values of minimum current one of which is zero give all the control necessary The resistances which are put in series with the thermostat are on the "maximum" current position zero or 10-ohms and on the minimum current position, 20-ohms or infinity The resistances can be controlled by two switches.

The joints in all connecting tubing should if possible, be free from rubber connections

A convenient relay for use with this thermostat is of the mercury in-glass type, the I A C RNK being one form which has a pilot relay working the main circuit breaker As previously stated, the use of a thermionic-valve arrangement to work a relay considerably lessens troubles due to sparking at the U tube contacts

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CHAPTER 3

Thermostats based on expansion of liquids—laboratory types

THE expansion of liquids with increase of temperature is used as a means of control in a number of laboratory and commercial thermostats of various forms. The movement of a column of liquid with the expansion and contraction of a volume of liquid, contained in a bulb immersed in the heated space or bath, is arranged to control a burner gas-supply or to actuate contacts in an electrical heating-supply circuit. The liquids are usually of the volatile class, as these have a high coefficient of expansion. Regulators controlled by mercury expansion are described in a later chapter.

Liquids for use in regulators

The liquid commonly used is toluene. When the temperature to be regulated greatly exceeds 100° C, however, the toluene must be replaced by another liquid, such as aniline or mercury. This modified form is not as sensitive as that containing toluene, in that the coefficient of expansion of mercury, for example, is much less than that of toluene, one litre of mercury increasing in volume by 0·18 ml for 1° C rise in temperature, whilst 1 litre of toluene increases by 1·1 ml for the same rise of temperature.

Coefficients of expansion at a temperature of about 25° C of a few suitable liquids are given in the accompanying table—

	Increase in volume of 1 litre for 1° C rise in temperature	Specific heat
	ml	
Water	0·25	1·0
40 per cent Calcium chloride solution	0·50	0·63
Mercury	0·18	0·03
Carbon tetrachloride	1·1	0·2
Toluene	1·1	0·4
Ethyl alcohol	1·1	0·5
Ethyl ether	1·1	0·55
Chloroform	1·3	0·23
Benzene	1·2	0·40

LIQUID-EXPANSION REGULATOR DESIGNS

In the form of regulator extensively used in the laboratory, the toluene or other liquid is contained in a glass bulb or series of bulbs Where it is desired to have a larger exposed surface, a glass spiral or a long length of closed ended tube, bent into a convenient form, may be used Various other means have been suggested to increase the ratio of the exposed surface to the volume of sensitive liquid, and so increase the response to temperature-changes A simple method is to make a number of thin walled indentations or depressions in the walls of the bulb, the bulb is not made more fragile by this means To ensure that air is not trapped beneath the indentations when the regulator is being filled, the tips of the indentations may be pointed slightly upwards, care should then be taken that air is not trapped in them when the regulator

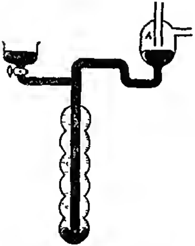


Fig 7 —One form of toluene-mercury thermostat for use with gas heated bath

Fig 8 —Arrangement to prevent creeping of toluene to mercury contact-surface

is immersed in the bath liquid, as this will nullify their usefulness to some extent Another suggestion to increase the sensitivity of the bulb is to place in it a good conducting metal foil such as copper

When liquids other than mercury are used as the heat sensitive liquid, it is usual to arrange that a column of mercury is moved by the liquid in order to provide a more positive means of control when using gas, and a conducting path when using electrical heating If toluene is used as the sensitive liquid it should, before use, be kept in contact with mercury for several weeks with occasional shaking, followed by redistillation over sodium, although the latter treatment is not recommended by some authorities Fig 7 shows one arrangement of the bulbs and mercury column. Hermetically sealed into the bulbs

is a tube containing mercury, reaching to the lowest bulb, where it dips into a small quantity of mercury.

Where the same continuous tube contains both toluene and mercury, as in some forms of thermostat, it is difficult to prevent the toluene from creeping around between the mercury and glass walls on to the surface of the mercury, unless a device [1] similar to that illustrated in Fig. 8 is introduced. By this means the ends of the tubes connected with the mercury and toluene dip well into the respective liquids and the side tubes facilitate filling with the appropriate liquids. The lowest tube in Fig. 8 is connected to the bulbs containing the remainder of the toluene.

It may be mentioned here that the regulator bulb need not necessarily consist of glass. Steel,[2, 3] copper,[4] and especially Monel metal [5] have been recommended, the latter on account of its strength, resistance to corrosion, and greater rapidity of response to temperature-changes. When electrical heating is used with the bulb of metal, it is necessary, as will be seen later, that the upper part of the regulator shall consist of glass. The junction between the glass and Monel metal may be made by nickel plating. The glass is first coated with a silver mirror, copper-plated and then soldered to the Monel metal bulb. The joint is next plated with a thin layer of copper and finally with a thick coat of nickel.

When once fitted up, the quantity of toluene in a regulator is not usually altered ; but the level of mercury has to be altered for adjustment purposes. This may be done in various ways,[6, 7] one way being, as shown in Fig. 7, to connect the column of mercury by a side tube to a reservoir of mercury. A sensitive method of adjustment is to dispense with the reservoir and to close the side tube with an airtight rubber bung through which passes a glass plunger dipping into the mercury. The diameter of the plunger is only slightly less than the internal diameter of the side tube ; Jena K.P.G. is of very uniform bore. Raising or lowering the plunger moves the mercury column. The space between the mercury and bung in the tube is filled with a mixture of one part water and two parts glycerine. This serves to exclude air and at the same time lubricates the plunger.

Gas-heating type

Where gas is used as the source of heat for the bath, the mercury column (see Fig. 7) emerges into a bulb into which the gas is delivered by the tube *A* close to the surface of the mercury and then passes away to the heater by a side tube *B*. The tube *A* should be centred and cut off square. Another method is to taper and grind the tube so that a long, narrow hole is formed, making an angle with the mercury surface.

On increasing the temperature of the toluene, expansion takes place, forcing up the mercury in the tube and partially or wholly closing the inlet tube and

on the principle of the differential manometer, and temperatures from about 15° C to 40° C can be maintained with its aid Fig 12 illustrates diagrammatically this type of regulator The vertical tubes would in practice be suitably disposed to make the construction more compact in form The bulb of about 3 cm diameter is first completely filled with isopentane or other volatile liquid, and then half the volume of the isopentane in the bulb is replaced, with the aid of a capillary tube, by some inert gas such as nitrogen or hydrogen Finally mercury is added to both limbs The bulb is then heated to displace sufficient isopentane so that both columns of mercury just meet at the apex of the inclined fine-bore tubes when the regulator is cooled nearly to the control temperature required Further adjustment can be made by the addition of mercury Fine adjustment can be facilitated by the aid of a small plunger in one limb The electric current is broken with rise in temperature, so that a relay is not really necessary The sensitivity of the regulator will be governed by the amount of inclination of the inclined tubes This form of regulator is somewhat difficult to set up and has a narrow range of temperature-control The form of regulator described in the earlier part of this section is used almost universally for electrical-heating control

CONTACTS

One of the chief difficulties, and one which largely governs the sensitivity of the normal toluene mercury type of thermostat, is that of obtaining a suitable arrangement for making and breaking the electrical circuit in the regulator

Failure at the electrical contact may leave the heater operating at its maximum capacity causing the bath temperature to rise and forcing the mercury and sometimes even the toluene out of the bulb, and necessitating a large amount of work to set in order again Contact failure is generally due to fouling of the mercury surface

If the mercury does not wet the contact wire, an extremely small rise or fall of the mercury thread will be sufficient to make or break the circuit. Mercury adheres to platinum so that if this material is used as the contact wire the breaking of the circuit takes place at an appreciably lower temperature than the make The use of iron, tungsten, nickel or nichrome in place of platinum effects an improvement in this respect, and the make and break occur at temperatures closer to one another Decreasing the bore of the contact tube tends to increase the sensitivity of the thermostat, but a tube diameter of less than 1 mm may cause erratic working, for the following reason the time lag in most systems is such that the mercury overshoots and undershoots the contact point, and when the mercury is forced up between the wire and the glass in a small capillary, the mercury column is apt to break and the thermostat then begins to operate at a new temperature

Gouy oscillating contact

Gouy[10] observed that if the contact needle, instead of being fixed, is given an oscillating motion of 20 seconds' period along the axis of the tube, the sensitivity of the regulator is improved[11] Incidentally, the period of oscillation need not necessarily be this figure

Energy is in this way periodically supplied to the bath when contact is made between the mercury and the needle An increase in the temperature of the thermo-regulator bulb results in a rising of the meniscus, which causes a decrease in the length of time during which energy is periodically supplied to the bath, thus tending to stabilize the bath temperature Gouy stated that the use of this device greatly reduced the errors due to the compressibility of the thermostatic fluid and to the distortion of the mercury meniscus as it moved up and down

Sligh[12] has made a theoretical analysis of the fixed and oscillating types of contact and has put forward equations to represent the conditions which might be expected with the use of each type The equations are based on the assumption of a constant time-lag, coupled, as it were, with a bath of perfect conductivity

Mathematical representations

(*a*) *Fixed contact* —The periodic change in temperature as the regulator operates with a fixed contact is expressed by the equation

$$\Delta\,\theta_p = \frac{tW}{M} + \Delta\,\theta',$$

where $\Delta\theta_p$ is the total change in temperature during one cycle of " make " and " break," that is, the amplitude of the periodic oscillations of temperature , and t is the time-lag of the thermo-regulator in seconds This quantity is defined as the number of seconds which would elapse between the time when the total energy input to the bath has reached a value corresponding to a given meniscus position and the time when the meniscus assumes this position, supposing the rate of energy input to be approximately constant It is assumed that the lag of the bath as a whole with respect to the heater is less than the lag of the thermo-regulator with respect to the heater W is the maximum electrical input supplied by the regulator in watts, and does not refer to the average input

$\Delta\,\theta'$ is the contact lag , that is to say, the change in temperature required to change the contact of the thermo-regulator from " make " to " break " This quantity can be very variable M is the heat capacity of the bath in joules per degree.

The changes in the mean bath temperature, $\Delta\,\theta_m$, produced by changes

in the thermal head, $\Delta \varphi$, and by changes in the maximum electrical input controlled by the regulator, ΔW, are represented by

$$\Delta \theta_m = \frac{t}{2M} \quad \Delta W - t K \Delta \varphi,$$

where φ is the portion of the thermal head of the bath (i e the difference in temperature between the exposed portion of the bath and its surroundings) which is compensated by the thermo-regulator This does not include the portion of the thermal head which is compensated by the fixed heating φ is considered positive when the bath loses heat to the surroundings K is the cooling constant of the bath in degrees per second

(*b*) *Oscillating contact*—The corresponding formulæ for the oscillating contact are as follows—

For changes in mean bath temperature $\Delta \theta_m$, due to changes in thermal head, $\Delta \varphi$, and changes in average electrical distribution along the path of the moving contact, ΔW,

$$\Delta \theta_m = \frac{M K \varphi}{a W_1 W_2} \Delta W - \frac{M K \Delta \varphi}{a W_2},$$

where a is the sensitivity of the thermo regulator, i e the movement of meniscus in cm per degree change in temperature, and W is the electrical energy distribution along the path of the oscillating element, expressed in watts per cm i e a change of 0 1 cm in the position of the meniscus would change the average power input by $W/10$ watts

The subscripts 1 and 2 denote values before and after changes in the length in centimetres of the path of the oscillating contact over which energy is being delivered to the bath

The expression for the variation in bath temperature as the regulator operates was not derived, but Sligh states that from experiment this variation was found to be small

Operation of oscillating contact

For successful operation of an oscillating contact thermo-regulator, the following conditions are necessary—

(1) The periodicity of the oscillation should be small in comparison with the lag of the bath, say one-fifth of the value, but not so small as to produce sustained waves on the mercury surface There seems to be no advantage in reducing the period beyond that necessary to damp the periodic fluctuations in bath temperature sufficiently to render their effects imperceptible

(2) The length of path of the oscillating element should be large in comparison with the movement required to make or break contact with the mercury surface, one mm seems to be sufficient in most cases

(3) The energy distribution along the path of the oscillating element should be large in order that great range and close regulation may be secured under a wide range of external conditions. The upper limit to this energy distribution is fixed by the fact that the smallest amount of energy which may be supplied during a single cycle should not exceed that which is required during that cycle. If this condition is violated, motion of the meniscus beyond the limits of the stroke of the oscillating element would result.

White [13] considers that it is unnecessary to add the temperature-lag of the bulb at the end of the stroke. With the ordinary mercury-contact, thermostat regulator, it is sufficient, he considers, if the total lag, expressed as a temperature-difference, is not over twice the "backlash" equivalent, but already gives twice the correct result when the ratio of the lag to the equivalent is 20. The backlash equivalent indicates, in degrees, the difference in temperature at which contact "makes" and "breaks," the former taking place for a higher temperature than the latter. The maximum inconstancy normally occurring in an ordinary thermostat for any given rate of heating is the periodic oscillation of temperature for equal resultant up-and-down rates. White expresses this oscillation by the equation

$$\frac{\Delta U_B}{V L} = \frac{v T}{2 v L} - \tanh \frac{v T}{2 v L},$$

from which the ratio of $v T$, the oscillation, to the temperature-lag, $v L$, or to the backlash equivalent, U_B, can be found for any ratio of ΔU_B to $V L$. V is the rate of heating due to the heater alone, v the instantaneous actual rate, here equal to $\frac{V}{2}$, and L is the time-lag.

Advantages of oscillating contact

The principal advantages of the oscillating-contact type of regulator over the fixed-contact type may be summed up as follows—

(1) A large amount of available energy can be used to compensate for any possible wide fluctuation in external conditions without a sacrifice of closeness of control.

(2) A bath temperature is obtained in which the periodic variations about the mean due to operation of the regulator are very greatly reduced.

(3) Troubles due to soiling of the mercury, surface sticking, etc., are greatly reduced. Nevertheless it must be stated that the mercury tends to become fouled sooner with this form of contact than with the stationary form, and requires fairly frequent cleaning.

The advantages to be secured by the use of the oscillating type of regulator are due to the fact that the time at which a given movement of the meniscus may affect the energy input is rendered independent of the physical constants

of the bath, and is made dependent only upon the periodicity of the oscillating element of the regulator Further advantages accrue from the provision of a means for applying successive corrections, at short time-intervals, to the value of the energy input, instead of corrections at such longer time intervals as will permit of wider excursions of bath temperature above and below its mean value

The Gouy contact was the first device to bridge the gap between simple on and off control and continuous control It is used in modified form in many present-day controllers

The mercury surface may be oscillated,[5] instead of the contact wire, to effect a result similar to that of the Gouy arrangement Such movements have been produced [14] by trapping pockets of air with the mercury in the arm carrying the stop-cock and reservoir, and by supporting the regulator in such a way that the vibrations of the motor used to stir the bath liquid are imparted to it, or a time delay device (see p 180) may be used

A Sunvic unit which can be attached to the head of the regulator causes the upper contact to be drawn out of the mercury by means of a bimetal When contact between the mercury and upper contact is made the relay opens cutting off a bimetal heater coil and also the bath heater The bimetal will cool and raise the contact out of the mercury and switch on the relay, etc, again This will re-heat the bimetal which will then open the circuit—and so on As the mercury rises, the bimetal will take longer to cool sufficiently to raise the contact out of the mercury and so re close the heater circuit So gradually the ratio of the "on" to the 'off' time of the bath heater will decrease until it balances the heat losses This is a form of proportional" controller (see p 56)

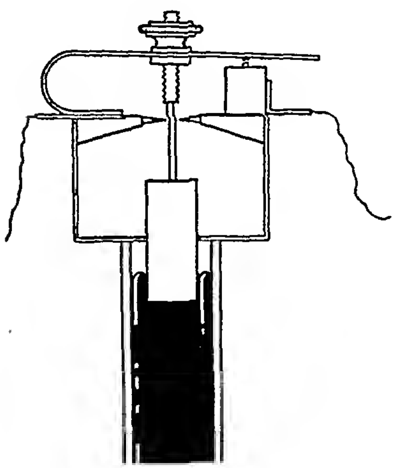
The mercury surface

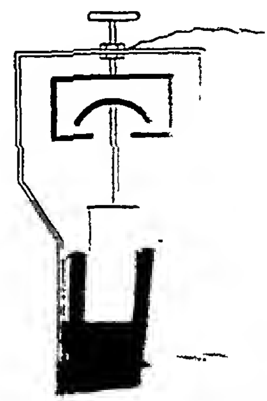
Whatever type of contact is used, it is necessary, for high sensitivity and satisfactory working, to maintain a clean mercury surface at the contact This requirement is not easily attained, and many methods have been tried

Elimination of oxygen from the space around the contact would be a satisfactory method With this object in view, the air has been replaced by hydrogen or nitrogen This method is satisfactory as long as the gas is present, but is cumbersome because of the apparatus and care required to maintain the gas There is a risk of forming an explosive mixture with air which may be admitted inadvertently when hydrogen is used Generators have been specially designed [15] to supply the necessary hydrogen If the regulator is sealed [16] it is difficult to change the position of the contact-point and also impossible to oscillate it It does not, however, prevent the mercury surface from being agitated by vibration of the regulator Sealing [17] the cap of the regulating capillary with a drop of mercury fails if the regulator is jarred, because the drop then works downward

It may be mentioned here that all regulators which depend for their action on the expansion of a column of liquid are sensitive to fluctuations in barometric pressure if the liquid is open to the atmosphere. Variations in the controlled temperature of the order of $\pm$ 0·2° C arise from this cause. By sealing the gas space above the liquid surface to maintain the inert atmosphere, variations due to this cause are therefore prevented. Another method [18] of eliminating atmospheric pressure variations may be mentioned which is to place in the bath a vessel of about one-litre capacity containing air, and to connect it by a tube with the top of the regulator. The junction between the tube and regulator can be effected by arranging a mercury seal around the top of the regulator into which the tube dips. The latter method does not, of course, prevent the mercury surface from coming into contact with oxygen.

Prevention of sparking at mercury surface





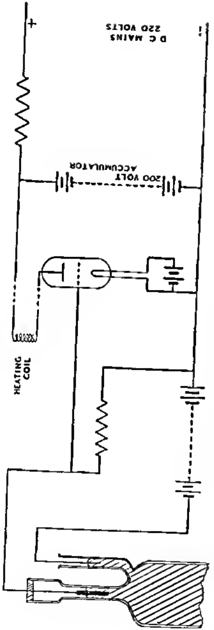


Fig 15 —Winton variable-contact resistance and thermionic-valve relay

is necessary, but a continuous, uni-directional flow across the working space is to be avoided, since under the latter conditions a temperature-gradient is set up in the space by the air-stream, which is continuously losing heat.

If a single large source of heat is used, and particularly if this source be incandescent, there is a risk that direct heating of the contents of the space may occur by radiation. A number of small heating elements is preferable, and heaters of the wire-grid type very often meet the case. The risk of fire, however, is present with this type of heater, and the use of a number of small heating lamps may sometimes be preferable. In this way the temperature of the heating elements need only be a few degrees above the control temperature.

Multi-jacket chambers.—The use of a double-walled vessel, with the space between the double walls thermostated and the whole of the air in the inner chambers thoroughly stirred, permits of very close uniformity and constancy of temperature.

Tian,[27] suggested as the controlled space, the centre of a system composed of several jackets placed one inside the other. Each of the jackets would be thermally insulated from outside and filled with water or other liquid. Only the outside container should be provided with a thermoregulator and relay. In principle this is the only jacket which is subjected to the direct exchange of heat with the surrounding room and the air in it.

It has been proved that in a three-jacket system the temperature fluctuations in the central space are very small.

There are, however, inconveniences associated with a multi-jacket thermostat. First, a long time is necessary for the whole system to reach thermal equilibrium due to the large thermal inertia. This delay may be minimized by inserting an electric heater in the central vessel to establish in advance the temperature expected to be the final one, corresponding to the equilibrium between the inside and outside jackets.

Another inconvenience, where very close temperature control is desired, is associated with small variations in the average temperature of the outside vessel due to various causes. When a slight alteration of temperature thus occurs, the whole system has to readjust its thermal equilibrium, therefore the heat exchange proceeds until the temperature in the whole system reaches its new level. If some hours later a new change occurs in the average temperature, the thermal equilibrium may be disturbed once more, even before the system has reached its new equilibrium occasioned by the first slight alteration of temperature. It may therefore happen that the central system will never reach any permanent state of equilibrium and will be subject to small fluctuations of temperature, each of them extending over a long period.

However, the fluctuations in the central container are actually very small, and the apparatus is really a thermal damping system with the temperature fluctuation waves losing amplitude as they penetrate the interior.

Ward [27] using this type of thermostat succeeded in maintaining a constant temperature with an accuracy of 0 000002° and it appears that for short duration experiments this method is almost ideal

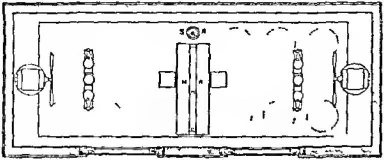
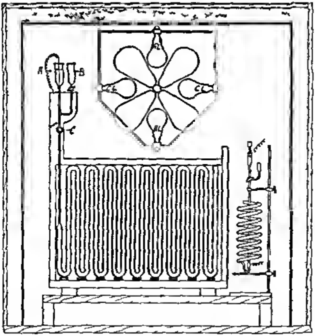


Fig 16 —Plan of thermostated air-chamber
Sl ng sect on throu„h fans l eat ng lamps ma n and subs d ary toluene regulator

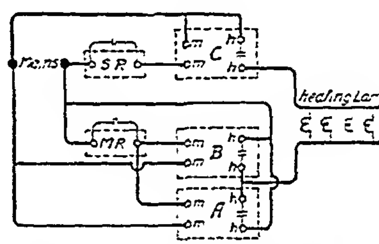


F g 17 Transverse section through thermostated air-chamber
Sho ng ma n and subs d ary toluene regulators heat ng lamps and fan in rear

Thermostated air chamber—A detailed description of a thermostated air chamber (see Figs 16 and 17) has been given by W H J Vernon [28] The chamber is of wood 96 in long 45 in h gh and 39 in wide lagged with cork

slabs. Two fans, situated one at each end of the chamber, force air over a group of heating lamps set in front of each fan. The two opposing air-streams meet in the middle of the chamber and pass downwards over the regulator bulbs. A portion of each stream then passes through two holes in the working floor, under which it returns.

In the work for which the Vernon thermostat was primarily designed, it was of importance that the controlled temperature should be maintained over long periods without risk of breakdown, even of a temporary character. A special system was therefore introduced to avoid such a contingency. Normally, the main regulator (*M R*) (Fig. 18) works in conjunction with the two main relays (*A* and *B*), which are connected in parallel. If either of these fails in such a way that the heating circuit is broken, the other carries on at the temperature controlled by the main regulator. If, however, the failure of either *A* or *B* should result in the heating circuit being permanently "made," the temperature would steadily rise, notwithstanding that its partner would cease to operate. The subsidiary relay *C*, however, is arranged so that its heating circuit is in series with the heating circuits of *A* and *B*; it is operated by the subsidiary regulator (*S R*), which is adjusted to take control as soon as the temperature reaches a value very slightly higher than the normal working temperature. The margin of temperature may be adjusted to quite a small fraction of a degree, and warning of the trouble is given by the subsidiary relay coming into operation.



MR - Main Regulator   SR - Subsidiary Regulator
A & B - Main Relays   C - Subsidiary Relay.
m - Magnet Circuit Terminals.
h - Heating Circuit Terminals
÷ - Condensers.

Fig. 18.—Electrical connections of Vernon thermostat

Bath liquids

The choice of bath liquid depends on a number of factors. Consideration has to be given to the suitability of the liquid for the temperature-range in which it is to be used, and also to the heat capacity, which should be as high as possible. A liquid which does not fume at the temperature of operation should be selected if possible. A useful property in the liquid is that of retaining its transparency after long usage, and if it is easy to remove from glassware and metal objects, so much the better. A factor which must not be forgotten is the risk of fire when certain materials are used at temperatures too near their

flash-points Some of the commonly used liquids are listed below, with upper and lower temperature limits—

	Temperature range °C
Water	0 to 80
Kerosene	−40 „ 75
Brines	−40 „ 120
Light lubricating oils	30 „ 200
Commercial vegetable fats	100 „ 300
Glycerine	100 „ 270
Tempering oil	50 „ 300
High-temperature lubricating oil	100 „ 300
Lead-tin alloy	200 „ 600
Fused inorganic salts	200 „ 1600

When water is used as a bath liquid, a slimy growth is apt to form after some time This may be prevented by suspending in the bath a muslin bag containing mercuric iodide, or by dissolving a little mercuric chloride in the water Evaporation of the water may be minimized by maintaining a layer of olive oil on the surface

Brines and aqueous solutions of salts may attack the walls of the containing vessels on account of hydrolysis, and moreover with brines the maximum limit of temperature is only about 20° C above that of boiling water

Sulphur has a tendency to fume and therefore requires the use of a hood, also care has to be taken in handling it when hot Otherwise it makes quite a good bath liquid and is often used

Paraffin oils and bath waxes [30 1] must of course be heated with due regard to the fire hazard "Hard" hydrogenated vegetable oil is a good bath-liquid, since no tarry masses are produced in use and the risk of fire is small So called "hard sesame oil," an opaque, white solid, melts at 60° C to a clear oil and has a weak "flash" at 320° C This substance does not stick to iron or glass on solidifying, but cracks and falls apart into fragments, and it is superior to vaseline, paraffin or other hydrocarbons as a bath liquid Hard hydrogenated cotton seed oil is more widely obtainable than the sesame product

The upper temperature limit of the oils is set by the decomposition which occurs at higher temperatures, large volumes of gas with a disagreeable odour being given off and spontaneous ignition often occurring For moderately high temperatures, the difficulties may be obviated to some extent by enclosing the oil or paraffin in a metal vessel communicating with the air through a single tube, through which the stirrer spindle passes, the tube serving as a kind of reflux condenser With an oil bath it is possible to have a number of tubes closed at the lower end and let into the bath through the cover, thus forming a number of air baths of considerable capacity and with excellent uniformity of temperature

Lard is said to be more satisfactory than heavy mineral or vegetable oils. An iron pot serves as a containing vessel.

The eutectic of diphenyl-diphenyl oxide may be used as a bath liquid up to 200° C. Silicone fluids are also useful between −48 and 600° C.

Beattie recommends the eutectic mixture of lithium, sodium and potassium nitrates, which consists of 30 per cent lithium nitrate, 14 per cent sodium nitrate and 56 per cent potassium nitrate by weight, and which melts at 120° C. A less expensive mixture consists of 27·3 per cent of lithium nitrate, 18·2 per cent of sodium nitrate and 54·4 per cent of potassium nitrate, a mixture which is fluid at 135° C, although some solid separates. The specific gravity of the latter liquid is 1·85. It is advisable to allow the liquid to act on steel turnings for several weeks before using, in order to minimize corrosion and other effects.

Many other inorganic salts are available for use as bath fluids.

Metaphosphoric acid, melting at a temperature of 150° C to a clear liquid, can be used as a bath liquid, but is improved by the addition of 85 per cent orthophosphoric acid. A variety of mixtures of the two acids can be employed, but the most serviceable is that consisting of 4 parts of 85 per cent orthophosphoric acid to 1 part of metaphosphoric acid. This mixture can be used in the temperature-range 100-340° C. The mixture is mobile at room temperature and, in common with other mixtures of these two substances, possesses a very small temperature-gradient, as expansion takes place on increase of temperature, which serves to circulate the liquid. It is advisable to heat the mixture to a temperature of 260° C and to remove all the water vapour before putting into use.

When substances which are solid at ordinary temperatures, such as metals[23] and alloys,[24-7] are used as bath liquids, precautions have to be taken that the bath is heated from the top when melting, so that liquefaction occurs from the surface of the solid downwards. If melting starts at the bottom, the expansion may cause fracture of the containing vessel. It should also be remembered that the vapours of some metals, such as antimony and lead, are poisonous.

Other objections to baths of metal are their relatively low heat capacity and high specific gravity.

Containers.—The size and shape of the bath will be determined by the contents, and liberal allowance should be made for adequate circulation of the fluid. The material of which the bath is constructed is determined also by the contents: glass, iron, galvanized iron, zinc and copper baths are used. Enamelled iron usually cracks and rusts after a short time, especially if used at the higher temperatures.

Glass-sided troughs[28-9] can be readily made to any form with the aid of metal angle or channelling framework. Lead-oxide base cements[29] are most suitable for the joints.

Tanks made of "Perspex"—clear transparent methyl methacrylate—are very convenient in that they are easily fabricated, light in weight and tough. The thickness of the material may be chosen to suit the size of the tank; for a two foot cube capacity, material approximately $\frac{3}{8}$ in thick would be required, but for a one-foot cube a $\frac{1}{4}$ in thickness would be suitable.

The tanks are made by carefully machining the base and sides so that they form an accurate fit. The sides are then fixed together by soaking the edges of two of them in chloroform and placing them in position on the corresponding pieces of Perspex thus forming a bottomless box. The lower edges of this box are then soaked in chloroform spread on a glass plate, and after softening for one minute are placed on the Perspex base with a weight of approximately two or three pounds so arranged as to distribute the pressure evenly. Alternatively Perspex cement No 6 can be used for jointing. After three or four hours, if the joints have been made properly, this tank should be water-tight and ready for use. It is preferable, however, to leave it over night before applying the full load of water. These tanks are suitable for temperatures up to 80 or 90° C.

It has been found desirable to eliminate the static charge which sometimes collects on dry Perspex sheets by applying a small quantity of Cirrasol S B which may be obtained from the I C I. For general cleaning purposes it is found that warm soap and water is quite effective.

Methods of stirring the bath liquid

Vigorous and adequate mixing and stirring of the liquid is essential in all thermostatically controlled baths, in order that temperature gradients set up in the region of cooling and heating may be smoothed out and the temperatures equalized. A rapidity of stirring just insufficient to produce wavelets and floating bubbles is generally found adequate. A Beckmann thermometer is convenient for exploring the bath for temperature differences; but it must be remembered that rapid local temperature fluctuations may occur which are integrated by a thermometer even of this type (because of its high thermal mass) and may therefore be undetected. It must also be realized that a stationary reading cannot always be taken to indicate a constant temperature. Despite vibration of the thermometer, "sticking" of the mercury may persist. Further, a "soaking" effect may arise. This occurs if the thermometer is left at room temperatures for some time; on returning to higher temperatures it rises too high, and subsequently *very* slowly sinks.

Fluctuations in temperature of the bath may occur, due to a number of causes; these factors have been dealt with in greater detail elsewhere (Chapter 1). There is a lag between the occurrence of a temperature change in the bath and a compensating change in the heating current and a lag before this change of current affects the temperature of the bath. These two effects

produce periodic fluctuations or "hunting" of the temperature. Slight irregularities in stirring may produce shifting temperature pockets in the bath, and this effect is aggravated if the heating is concentrated in a small localized area.

There are various means of stirring, to which brief reference will now be made.

Air-jets.—The use of air-jets is often a convenient method of stirring. For low-temperature work the air must be dried to remove moisture which otherwise would condense in the bath. The disadvantages of the air-bubbling method are the evaporation losses it causes; the heat carried into the bath in low-temperature work; and the heat taken from the bath at other temperatures by the air-stream. When the bath is in the form of a tall, cylindrical, vacuum-walled vessel, the use of an air-jet is often particularly convenient.

Screw propellers.—These stirrers mix the liquid well if several are used on the same shaft, but they are not very effective in driving the liquid over more or less pre-determined paths. The most suitable way of using screw propellers is to fix them so that the liquid shall be drawn from the top of the bath, where it has been exposed to the effects of disturbing influences, past the heating coils, then past the propeller, where it is thoroughly mixed, and finally discharged past the regulator bulb into the bottom of the bath. In this way a maximum rapidity of response to temperature-changes is secured which is essential to precise control, and the attempered liquid is brought into the working space in the bath with the minimum exposure to outside influences. As a general guide it will be found that good regulation is obtained with stirring set up by a propeller in a tube operating at such a speed that all the bath liquid passes through the tube three or four times a minute.

Centrifugal propellers give a wide range of velocities and force the liquid to the outlying parts of the bath.

Reciprocating paddles are ineffective as general mixers unless they are of relatively large size.

Supports for objects in bath

The stands for objects immersed in the baths should be perforated or latticed, in order that they shall not have any appreciable effect upon the circulation of the liquid.

The buoyancy of the immersed articles has to be overcome in some cases by loading or fixing down.

Gas heating of bath

Heating by gas is convenient and possesses the advantage of a low operating cost, but this is outweighed by a number of disadvantages. It is rather difficult

to deliver the heat from a gas flame to the exact positions where there is greatest loss of heat The problem of obtaining a burner which will not strike back, not cover the apparatus with soot, and yet burn with a good hot flame over a wide range of gas flows, is very difficult to solve One method is to provide the major portion of the heat by a Bunsen burner, with a small burner controlled by the regulator to maintain the desired temperature

Again, the question of danger from fire must not be overlooked, especially when the apparatus is left unattended over long periods of time Rubber tubing for the gas supply should be avoided

Electrical heating of bath

On the whole, heating of the bath by electricity, when available, is to be preferred to gas, for the heat can be delivered in approximately the position where greatest loss occurs and the controls are simple and positive

Heating by electricity may be achieved by immersing a number of incandescent electric lamps in various positions in the bath, and protecting the sockets from the action of the water by suitable means Electric lamps are manufactured with long stems especially for heating purposes A length of tube of 30–40 cm has a bulb at one end, and at the other, metal contact-pieces, collar, and studs as in an ordinary lamp Since heating, and not lighting, is required the lamps can be under run thereby increasing their life considerably A 250-volt lamp on a 200-volt circuit, with a nominal candle-power of 50, is suitable as a unit To overcome the buoyancy, a ring of lead should be slipped over the head, resting on the bulb

Coils of bare or covered wire may be wound around the bath or even immersed inside it , but in the latter case, with liquid baths, electrolysis tends to take place, which ruins the coils, even when using alternating current , hence it is always advisable to enclose the heaters for protection

Convenient heating elements can be made by inserting coils of nichrome wire in test tubes filled with oil It is sometimes an advantage to place an auxiliary heater near the regulator itself, and this can be done simply by fusing a length of tungsten wire into a tube of high melting point glass and bending to a convenient form

When oils or similar inflammable liquids are used as bath liquids, it is sometimes advisable to insert a safety device in the heating circuit Otherwise, the bath may become overheated if one of the components, such as the relay, fails This safety device can take the form of a fusible link in the electrical heating circuit The link is placed in a metal or glass sheath which is immersed in the bath, so that when the link melts it breaks the circuit and falls into the bottom of the sheath Fusible links of numerous components [40] and proportions can be made or obtained to suit any desired temperature

The method of making the bath liquid an electrical conductor and heating

by passing the current between resistant electrodes is not to be recommended, because electrolytic action may take place, and also the heat evolved is badly distributed. Baths of this type have, however, been devised. For instance, S. C. Collins[41] has described an arrangement for the automatic control of such a bath where one of the electrodes which conducts the electricity into the bath is contained in a pocket. The unbalancing of a U-tube arrangement containing ether and mercury, inserted in the bath, causes a glass plate which is attached to the tube to close the mouth of the pocket, and so to cut down the cross-section of the column of conducting liquid.

Another form of electrolytic heater[42] consists of glass tubing, of convenient length and bore, bent to fit the water bath and filled with sodium hydroxide. Two steel rods or wires, inserted into the two open ends of the glass tubing, serve as electrodes. The resistance of the heater is adjusted by varying the concentration of the electrolyte or the distance between the two electrodes. The current density at the electrodes should be limited to less than 1 amp/cm^2 otherwise a.c. electrolysis commences and the electrodes corrode. The electrodes also corrode in sodium chloride solution. Concentrated sodium hydroxide gives the best results. The heater tends to give out more heat at higher temperatures due to greater electrical conductance. The heater should not be used in air because it may be over-run.

General purpose electrical circuit

In addition to the electrical circuits already described with particular objectives, the circuit[43] described below will be found to be an arrangement with useful adjustments available (Fig. 19). The heater H for the bath is of

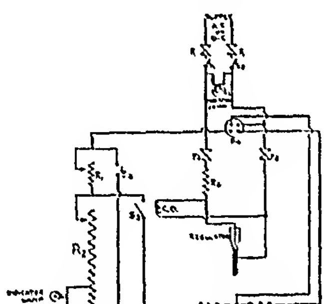


Fig. 19.—Circuit for electrical heating of bath

low heat capacity and is of the "three heat" type. It is operated through a "three heat" switch S_1. The resistance R_1 is the principal control resistance and R_2 is the auxiliary control. Both these resistances are short circuited by the switch S_2 when it is required to heat the bath quickly.

The auxiliary resistance R_2 is brought in or out of the heater circuit by the solenoid operated switch S_3 which is controlled by the thermoregulator through the solenoid *CO*. A small 4-volt lamp L_2 may be incorporated in the circuit to show when the resistance R_2 is in circuit, that is, when the thermoregulator is operating to cause a fall of temperature.

The solenoid is in series with a high-value resistance R_4 and the thermoregulator is connected across the solenoid. When contact is made in the thermoregulator, the solenoid is short-circuited, and the switch S_3 opens.

Fuses F_1 and F_2 protect the circuit from overload, and an indicator lamp L_1, connected through a resistance for direct current or a small transformer for alternating current shows when the circuit is functioning.

Operation.—With switch S_4 at "Full" and with S_2 closed the bath heats quickly. When the required temperature is approached, S_4 is turned to the "Medium" position and S_2 is opened, S_3 should now be closed unless contact has been made in the thermoregulator with S_2 closed, R_1 is adjusted to give a slowly rising temperature. At the desired temperature the thermoregulator is adjusted to make contact thereby opening S_3. With this switch open, R_2 is adjusted to give a slowly falling temperature.

After these adjustments have been made, no further alteration should be necessary unless there are large temperature disturbances.

Assuming that a 1000 watt 3 heat immersion heater on a 230-volt 50-cycle a.c. supply is suitable for heating the bath, up to a temperature of 210° F, the value of the variable resistance R_1 would be between 50 and 120 ohms, R_2 also a variable resistance, of about 30 to 300-ohms, and R_4 a fixed resistance of 7000-ohms. The switch S_3 can be an enclosed vacuum mercury switch, working in conjunction with the solenoid *CO*.

Insulation of bath

Good thermal insulation of the bath is essential, both for the conservation of heat and to minimize the effects of extraneous temperature changes. The form of insulation will of course be governed to some extent by the method of heating. Cork, either in the form of slabs, fine granules, shavings, or hair felt, can be used for this purpose up to moderate temperatures. Wood serves as an insulator, and its effect can be improved by filling the space in a wooden box surrounding the bath with some other insulating material, such as diatomaceous earth. When the size of the bath can be small, Dewar flasks may be used. A wooden case surrounding the flask serves as a protection and as a means of maintaining the temperature of the air around the flask moderately constant.

Constant level devices

To maintain a constant level to make up for evaporation, etc., various constant level devices are available[44,65] but the best known is based on

the Mariotte bottle principle in which a supply of water or other fluid in a reservoir is held back from running through a tube into the bath by the partial vacuum in the closed top of the reservoir. This vacuum is relieved when the liquid level in the bath falls below the level of the open end of another tube connected to the top of the reservoir.

Mention may be made here of a modified design of the air entry tube of the Mariotte bottle suggested by Holmes [52] for special applications where the level of a small quantity of liquid has to be maintained within close limits. With the normal design of Mariotte-bottle using ordinary laboratory tubing, the entry of air into this tube to relieve the vacuum causes the entire column of water to lift ahead of it and rush into the bottle. This may cause a volume of water to flow out far in excess of that required to restore the former level in the bath. Holmes has modified the air entry tube to prevent this action.

Some devices require drilling of the bath vessel which preclude their use with certain types of material, others require to be placed in a position easily accessible to a water tap and drain. They tend to waste water, sometimes even hot water. Again, if the water is not soft enough, distilled water cannot be used instead. For these and other reasons careful thought should be given when selecting a suitable constant level device.

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CHAPTER 4

Thermostats for use at atmospheric temperatures, employing regulators depending on the expansion of volatile liquids

WHEN the temperature of the space to be controlled is within the range of fluctuation of atmospheric temperature, cooling as well as heating arrangements have to be provided. The space to be controlled may be in the form of an air-oven or liquid bath.

Air-ovens

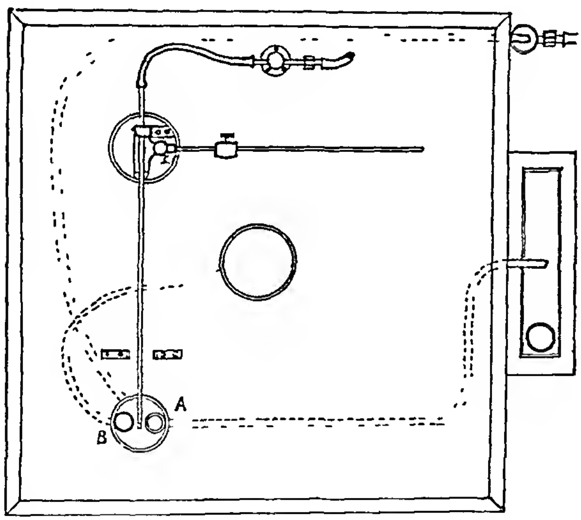

Fig. 20.—Incubator with provision for cooling or heating circulating water

An example of the air-oven type is the Hearson apparatus (Fig. 20). It consists of a water-jacketed chamber, a vessel containing ice, and a heater, the whole apparatus being thoroughly heat-insulated. The regulation of the temperature within the chamber is effected by a small stream of water which runs continuously through the apparatus by one of three courses, the particular

course being determined by the thermostatic capsule These three courses are—

(1) Heating passage through a boiler,
(2) Cooling passage through ice,
(3) By-pass passage direct to waste

The stream of water is supplied through a horizontal tube which is bent over at the end and pivoted so that, as it moves from side to side, it passes over the open ends of two adjacent vertical pipes If the chamber is being heated, the water from the tube passes through the right vertical pipe *A* and through the heater, where it is warmed before entering the water-jacket of the chamber When the desired temperature is attained and the necessary adjustments have been made, the tube is moved over to the left by the capsule-actuated lever, and the water flows into the space between the vertical pipes and so to waste, without affecting the incubating chamber If the temperature of the room is higher than that required in the incubator, the horizontal tube will continue to travel towards the left, so that the water runs down the left-hand pipe *B* and passes through the ice-box, where it is cooled, and then into the water-jacket, so lowering the chamber temperature to the desired point, when the capsule will partially collapse and cause the stream of water to pass again between the two pipes

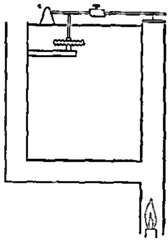

Fig 21 —Air-oven
Showing main heating flue and capsule controlling by pass flue

The makers appreciate the fact that should the water supply fail, the incubator control will not function, and they have devised an apparatus to obviate the use of running water where there is any risk of its failure By means of a two-way switch connected to the capsule lever, current is switched on either to heating coils in the oven or, if cooling is necessary, to a motor which drives a pump to circulate water in the jacket over a supply of ice

When the temperature required in an oven is always slightly above room temperatures, cooling is unnecessary and a simpler arrangement can be used, for most incubators this meets the temperature requirements The control generally consists of a capsule containing a volatile liquid placed in the heated space, the expansion of the capsule causing movement in a weighted lever which opens or closes a gas valve or makes or breaks contact in an electrical circuit

In a form of oven where the heating is by means of a burner, the control

can be very simple. For instance, the hot gases from the burner may proceed either directly through a vertical flue at the side of the oven or may be by-passed so as to flow around the oven and heat it (Fig. 21). The direction of flow is controlled by a capsule-controlled damper which closes the top of the direct vertical exit when the temperature falls. When equilibrium is reached, the damper hovers just above the exit and permits a portion of the hot gases to escape.

Water-baths

In order to cool water-baths, tap water, previously cooled if necessary, is either added to the bath or passed through pipes immersed in the bath.

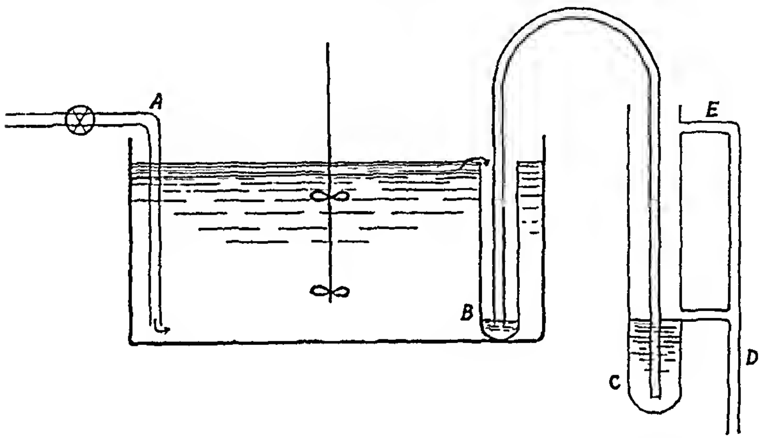

Fig. 22.—Siphon arrangement to maintain constant level in water-bath

Efficient stirring must, of course, be maintained. The flow of water to the bath may be controlled by modifying a toluene regulator of the gas type (Fig. 7). Cooled water is used instead of gas, and a rise in the mercury column cuts off the supply of cold water to the bath and diverts it to waste. This method is for small baths only.

Siphon systems.—Baths which are cooled by the addition of cold water require some means of keeping constant the level of the water in the bath. A number of such devices have been described by Wilde [1] and take the form of siphons of various designs. The use of siphons eliminates the necessity for drilling a hole in the bath, as this may be difficult to carry out with baths made of certain materials. An interesting device working on the same principle has been described by Bencowitz and Hotchkiss [2] and is illustrated in Fig. 22.

Cold water is supplied to the bottom of the bath by the pipe *A*. Excess water in the bath flows into the closed-ended tube *B*, from which it is siphoned into *C* and runs to waste through *D*. This occurs when the head of water in *B* is sufficient to cause a displacement in the direction of *C*. The tube *E* is a safety overflow. The siphon does not break, as its ends dip into reservoirs of water in *B* and *C*, and flow only occurs when there is a head of water sufficient to cause a displacement in the direction of *D*.

Othmer flow-controller.—A controller to regulate the quantity of water added to the bath has been described by Othmer [3] (see Fig. 23). A vapour-pressure bulb, containing ethylene oxide, is immersed in the bath and connected to the flow-controller by a tube containing mercury. The level of the flow-controller is adjusted so that the vapour pressure of the liquid in the sensitive bulb at the set temperature forces the mercury high enough to submerge the inverted V-weir of the central tube.

Cooling water flows into the tube at the upper left side of the flow-controller and, when the mercury is below the level of the weir, down the annular space, up through the inner tube, and out through the discharge tube on the left to waste. As the mercury rises and throttles the flow through the weir, the water rises in the annular space and overflows through the tube on the right side, running directly into the stirred water of the bath.

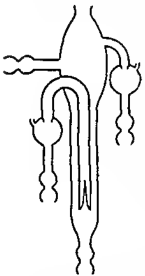

Fig. 23.—Othmer flow-controller

Both outflow tubes have unsealed tips to facilitate visual inspection of the comparative amounts flowing in each and are vented to prevent siphoning.

Control with a reverse action to that described is made by interchanging the connections on the left and right arms. For temperatures above that of the room, any temperature-point below that of the hot water available may be maintained with this arrangement. Hot water discharges through the left arm to supply the heat required. Ethyl ether is a suitable sensitive liquid for this range of temperature.

Baths for temperatures between 15° C and 25° C require provision for both heating and cooling. Two liquid flow-controllers are therefore used, one diverting a stream of cold water and the other reversed in action and diverting a stream of hot water, both controllers being connected to the same sensitive bulb in the bath. With the two weirs at the same height, increase of vapour pressure in the bulb raises the mercury level to throttle both simultaneously. This increases the cold water flow and decreases

the hot-water flow to the bath, the respective flows to waste changing to compensate.

The same controller can be used for other purposes. For regulating the gas supplied to a burner, the gas is introduced through the upper left arm and discharged through the lower left arm, all other openings save the bottom being plugged. Again, in distillation processes, the flow-controller can be adapted to control the stillhead temperature by regulation of the amount of wash liquid returned to a fractionating column.

Schmitt thermostat.—As an example of a thermostat using the principle of passing suitably tempered water through pipes immersed in the bath, that of Schmitt [4] may be instanced (see Fig. 24). Any temperatures within the

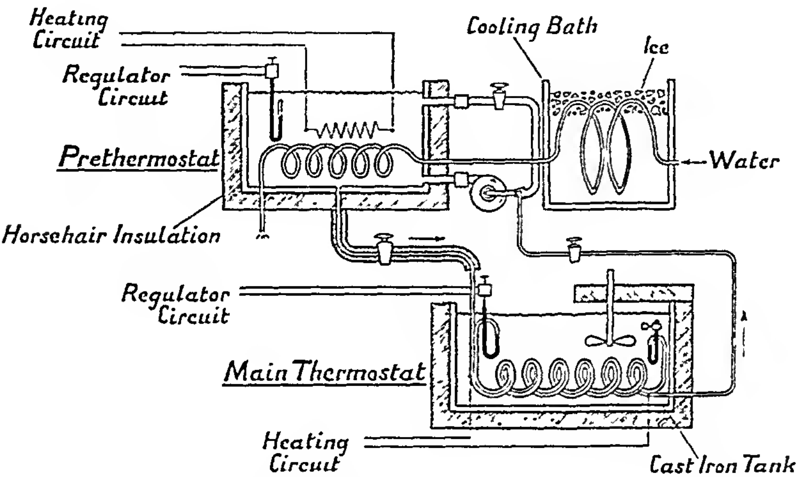

Fig. 24.—Thermostat for temperature-range between 10° C and 40° C

range 10° to 40° C may be maintained. The water passing through the coil in the bath is drawn from a pre-thermostat, which is regulated to a temperature just sufficiently below that of the main thermostat to provide adequate cooling when the water is made to circulate rapidly. The amount of cooling in the main thermostat is controlled by the difference in temperature between the pre-thermostat and the main bath, and by the rate of flow in the cooling coils, the latter being controllable by a valve. The pre-thermostat is cooled by the passage of ice-water from a constant-pressure system through a copper coil immersed in this bath, compensatory heating being obtained by a heating coil immersed in the bath and controlled by a toluene regulator. The temperature-difference between the two baths depends on the temperature desired. At 20° C the best results are found to obtain with a temperature-

necessary to obtain successful operation a somewhat full description will be given of the method they employed Fig 25 shows the regulator, together with the accessories for filling it All the components are of glassware, apart from the two contacts which are sealed in pyrex, one at *A* consisting of a

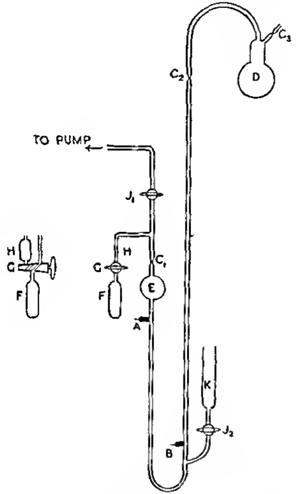

Fig 25 —Vapour-pressure regulator with accessories for filling

tungsten wire with a platinum tip, and the other at *B* of tungsten An important essential, and one on which the successful final operation depends, is that the glassware be thoroughly cleansed This can be done in the usual way with chromic acid, finally rinsing with distilled water After the glass system has been cleaned and then dried by sucking dry hot air through the

tubes, it is suitably supported to withstand the weight of mercury which is to be placed in it. Mercury is introduced into the retort D, and C_3 is sealed off. The system is then connected to a vacuum pump, with stopcock J_2 closed and stopcock G open to bulb F. When the pressure is as low as the pump will produce (preferably less than 0·1 mm Hg), heat is applied to the retort D and mercury is allowed to distil into the system. When the mercury has attained a height of 35-40 cm on each side of the U-tube, the heating is stopped. The bulb H is filled with carefully dried ether and the stopcock G turned to allow it to run into F. G is then closed and a little mercury put into H, to form a seal for G. The stopcock J_1 is closed and G opened to the system, when the bulb F can be very gently warmed (with the hand) until about 2 ml of ether have collected on top of the mercury column. During this process the mercury column on the ether side drops by about 25 to 30 cm with a corresponding rise in the other limb. The seal C_1 may now be sealed off, but in doing this care is required, or the ether vapour will blow out on heating ; it can be done in the following way. As much ether as possible is collected away from C_1 by cooling the system about A and E with ice or solid CO_2. The sealing can then be effected in the usual way. The cooling medium is removed and the mercury in D again heated. When the level of the mercury in the limb on the same side as C_2 is about 80 cm above the stop-cock J_2, the heating is stopped, J_2 opened slightly and the mercury allowed to flow into K, and the stop-cock then closed. C_2 may then be sealed off.

To set the regulator, the following procedure is adopted. Allow it to attain equilibrium in the room where constant temperature is desired, then open J_2 slowly and allow mercury to rise about 1 cm above the point A. If atmospheric pressure is low, it may be necessary to pump a slight amount of air from K to accomplish this. Close J_2. The regulator is then connected to a relay system governing the heat supply.

Yee [3] has modified Green and Loring's design to enable the regulator to be constructed elsewhere than in the place where it is to be used and also makes it adjustable over a temperature range of 20° C (20° to 40° C).

The regulator is shown in Fig. 26. A vapour chamber A has a bottom tube B sealed into it at C so that the liquid ether may be held in A. Tube D extends through A to the bottom of B and contains the mercury which is distilled over from P and the tube then sealed at Q. N holds the ethyl ether which is distilled into A, and its connection also sealed off, at S.

A fitting but freely moving plunger J actuated by a thumb-screw T, with a flexible seal K, allows the reservoir of mercury F to be put into communication or sealed off from D to allow adjustment of the mercury content of D and its connections. This is done by lowering the plunger below G to cut off the mercury in the reservoir when the room temperature is about 0·5° C below the required temperature. This plunger, moveable through a distance E,

is also used to make the final adjustment for the temperature control by forcing the mercury into the upper part of D until it barely reaches contact point H at the desired temperature

Other methods[4 7] of regulation of room temperature are possible, but in all cases the form of the regulator, the form of heating and method of mixing the air have to be carefully considered in relation to each other The importance of thorough mixing of the air cannot be over-emphasised

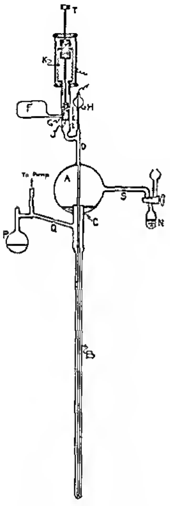

Fig 26 —Yee regulator

The necessary extreme turbulence of the air in the room is achieved by Deighton[4] by the aid of eight or more electric fans suitably distributed in the room One fan blows air over the elements of the fire or heater This is made of low heat-capacity by supporting three sets of nickel chrome wire resistances on *light, rectangular uralite frames* These resistances are placed one behind the other, vertically The expansion liquid used in the thermostat itself is paraffin acting on a column of mercury in a U tube The U tube contains the contacts The paraffin is enclosed in a long "compo" pipe which is fixed around the room about a yard from the floor, ending at the end remote from the U-tube, in a heat absorber of gilled copper tubing of a form similar to the old type of motor-car radiator This heat absorber, fixed immediately behind the heater, is a special feature of the thermostat and acts as a "brake" controlling the motion of the mercury in the contact tube after make and break of the current The heater owing to its small heat capacity, cools rapidly when the current is cut off, and when this occurs the fan in front of the heater blows cool air on to the heat absorber, causing contraction of the paraffin in it and thus offsetting the continued rise of the mercury due to lag Similarly, at 'make,' the heater warms up quickly and hot air is blown on the heat-absorber, causing the lag to be taken up as before The size of the heat absorber should be arranged so that the relay operates every 10 to 25 sec It is essential that, if variations of atmospheric pressure are not to affect the

thermostat, the whole of the "compo" tube and heat-absorber be filled with paraffin and free from air bubbles before sealing. A more uniform temperature in the room can be obtained if the heaters are split up as previously suggested and some of the heat is generated in the opposite part of the room. Suitable insulation of the walls of the room also assists in maintaining uniformity of temperature.

Solid-expansion thermostat for room temperature control

Mention may be made of a thermostat[5] which, while not dependent on liquid-expansion but rather on solid-expansion, is, however, used for room temperature control such as is considered in this chapter. The sensitive element, a stainless steel strip 80 ft. long, $\frac{1}{2}$ in. wide and 0·010 in. thick, is supported on pulleys around the walls of the room at a height of about a yard from the floor. Variations in length of the strip, magnified fifty times, cause a low-voltage relay to act which, in turn, through a magnifying lever of 6 to 1, causes the operation of a contactor to control a number of heating elements. In this way, slow movement of the first lever is converted, through the medium of the relay, into a rapid make and break in the second contactor, which controls a larger power-supply relay.

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CHAPTER 6

Mercury-expansion thermostats

THE mercury-expansion regulators described in this chapter are in a different category from those described in Chapter 3 in that, in the latter, the regulators considered are those which are solely used to control the temperature of an air or liquid bath for laboratory work In this chapter will be considered miscellaneous applications of the expansion of mercury in a somewhat different manner, for both laboratory and industrial purposes

Mercury thermometer type

One of the earliest, and still used, forms of thermostat, is that of a simple mercurial thermometer into which are fused two platinum wires connected in series with a battery and relay One platinum wire is sealed into the bulb and the other at a predetermined point at a certain height which represents a definite temperature, the mercury thread completes the electrical circuit at that temperature A suitable relay operates air, steam or gas valves as required This form of instrument was originally designed for such purposes as maintaining greenhouses at a fairly even temperature, the relay opening a cold air valve when the maximum temperature was reached

By sealing in a number of platinum contacts at various points along the length of the bore of the thermometer, any of these contacts may be selected, according to the temperature required

An adjustable form of instrument is available, in which one terminal is connected to a small spiral of platinum wire inside the bore A glass capsule containing a short piece of iron is located at the top of the thermometer tube, to which is attached a length of platinum wire passing through, and making contact with, the platinum spiral and forming the upper contact The capsule can be moved up and down in the tube by means of a permanent magnet applied externally and hence the regulator can be arranged to make contact at any temperature within the range of the instrument (See Fig 27)

These thermostats may be made to operate control valves through a thermionic relay

A maximum and minimum thermometer can be fitted with adjustable contacts and used to indicate by audible or visible means whether the temperature is too high or too low Another way in which this can be achieved with the ordinary type of mercury thermometer thermostat is to have "high" and "low" points For the "high-point" alarm an open circuit is used, which

the mercury itself closes as it reaches the upper platinum wire. For the "low-point" alarm a closed circuit is used, which the mercury opens as it recedes below the lower platinum wire. The alarm device is actuated by means of a relay which completes a secondary circuit when the mercury circuit is broken.

An apparatus depending upon the expansion of mercury to regulate temperature in a somewhat different manner, viz. by utilizing its mass, will now be described. This apparatus consists of a double-walled vessel, the space between the walls containing a liquid having a higher boiling-point than the temperature at which the space inside the walls is required to be kept constant. In this liquid is immersed a vessel full of mercury, with the outlet drawn out to a capillary tube, also full of mercury. The open end of this capillary tube dips into mercury contained in a cup which is attached to a ring encircling the outer vessel. This ring is balanced about a diameter by two pivots in the sides of the vessel, and is attached by means of a lever to the gas-cock. The ring is balanced for a required temperature by means of weights on its opposite side to compensate for the mercury ejected up to this temperature. When the temperature increases or decreases beyond the required temperature, mercury flows out of or into the vessel in the bath, unbalances the ring, and correspondingly moves the lever which controls the gas-supply valve. One of the principal difficulties in the use of this thermostat is that of obtaining a freely-moving gas-cock.

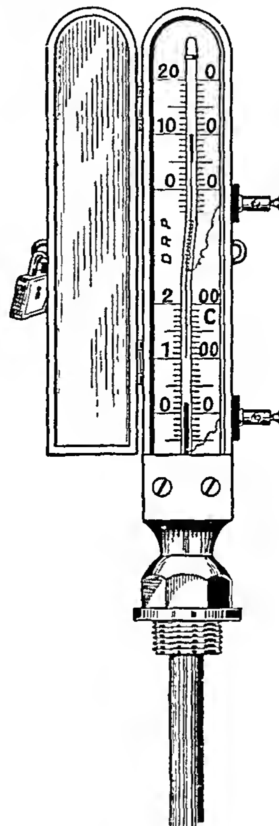

Fig. 27.—I.A.C. adjustable-contact type mercury-thermometer thermostat

Voltage regulator

A regulator has been devised by V. H. Stott,[1] which whilst not controlling the temperature directly, does so indirectly by keeping constant the root-mean-square voltage applied to the furnace terminals. It must be pointed out that the temperature of the furnace will not be maintained at a constant value where there are large fluctuations of room temperature over long periods. With the regulator in normal operation, the voltage remains at a certain minimum value (subject to mains fluctuations) for about 10 seconds, after which it is raised some 20 per cent and remains at the higher value for about the same length of time. The cycle is repeated

indefinitely and the times during which the maximum and minimum voltages are applied are adjusted automatically so as to maintain a constant mean square voltage per cycle The ratio of the maximum to the minimum voltage may be varied to suit different circumstances As the extra voltage becomes greater the time of a completed cycle of control becomes less the two magnitudes

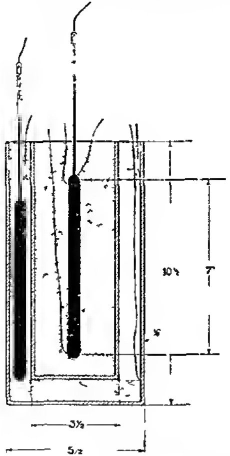

Fig 28 —Arrangement of mercury thermometers in Stott regulator

being roughly inversely proportional The cyclic period is too small to affect the temperature of a furnace of ordinary size

The regulator (Fig 28) consists of a bulb containing mercury, wound with a heating coil which in series with an adjustable resistance, is shunted across the points in the furnace circuit where voltage control is required * A platinum

* These points may either be the terminals of the furnace or rheostats may be included for convenience of control

wire is sealed into the bulb and another into a capillary tube projecting from the bulb. The bulb and capillary function like a mercury thermometer. The platinum wires are connected to the input side of a delicate relay containing a mercury-tilting switch. The output side of the relay is associated with the furnace circuit in such a manner that contact of the mercury with the upper platinum wire reduces the main furnace current. With suitable adjustment of the maximum and minimum currents, the temperature of the central thermometer is maintained automatically at 125° C. Energy proportional to that supplied to the central thermometer is supplied to the furnace. In order that this energy may be affected as little as possible by variations in the temperature of the room, the bulb with its capillary is placed in a large vessel,

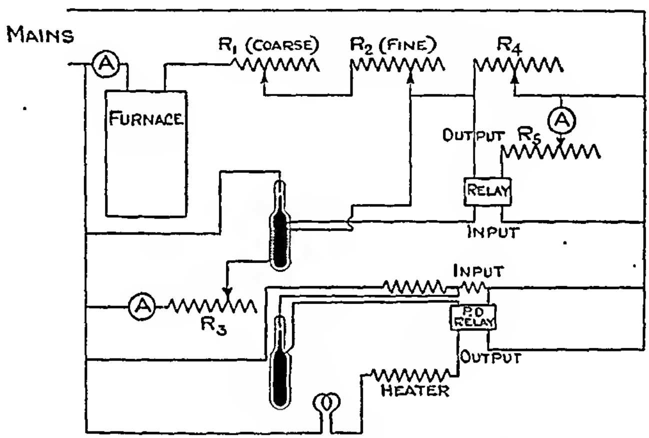

Fig. 29.—D.C. connections of Stott regulator

the annular space between the two being kept at a temperature of 50° C by means of a heating coil on the inner surface of the outer pot. The current through this heating coil passes through the output circuit of a post-office relay controlled by a mercury thermometer, so that thermostatic action is achieved.

The wiring diagram for d.c. mains is shown in Fig. 29. In the case of a.c. mains, direct current must be used to operate the relays. For a given value of R_3 it is possible to calibrate the furnace temperature, when in final equilibrium, in terms of R_1 and R_2. It is necessary to see that the proportional change of voltage produced by the regulator is considerably greater than any such change likely to occur in the mains voltage.

It is possible to adapt the apparatus for slow-heating or cooling.

After some experience with this thermostat, it was found that the end heat losses were greater than was originally supposed. They may be eliminated

by using a narrower and taller outer pot and arranging the lagging so that there is an air space round the top and bottom of the inner pot, as well as round the sides The narrower pot is placed eccentrically so as to leave room for the outer bulb The eccentric arrangement also facilitates the circulation of air by convection

Reference

STOTT *J Sci Instr* 1931 8 No 10 313 316

CHAPTER 7

Classification of control equipment

A LARGE proportion of industrial control instruments are of the pneumatically operated type. This system provides adequate power to operate all except very large, or high pressure, valves and thus meets most requirements. For the oil industry in particular, the absence of flameproofing problems makes the system particularly applicable.

Air operation enables the mathematical functions of modern temperature control to be very easily obtained with simple mechanisms. Hydraulic control mechanisms have not developed so rapidly and their use is chiefly confined to boiler control.

A recent development which has promising features is the use of oil with servo-mechanisms in conjunction with electronic measuring and amplifying systems (see p. 137).

Electrical control mechanisms are largely confined to electrically heated furnaces, although there are available electrically controlled valves to control liquid flow.

Before proceeding to a consideration of some industrial types of air-operated regulators, it may be advisable to explain some of the terms used in connection with regulators or controllers. Despite the tremendous variety of these instruments, the majority are based on three main methods of control, which may either be in their original form or in combination with each other ; a limited number of mechanisms employ derivations of these systems.

(1) The "on-and-off" method of control

Other terms applied to this category are : "two-position," "open-and-shut," "fixed-position" and the various "——stats." The French term is very apt : "*tout ou rien.*"

The on-and-off method of control is the most primitive and is characterised by the fact that the controls—meaning valves or contacts—can be in one of two positions. In one position the temperature is too low, and in the other too high. A sudden movement of the controls takes place from one position to the other. It is evident that a permanent oscillation of temperature must result, with an amplitude and frequency depending on the characteristics of the plant and on the extent of the variations in the conditions caused by the control. In the "three-point control," three positions are provided, one lying about half-way between the other two. The temperature is just correct

when the controls are in the middle position When the conditions change, to make the temperature depart from the desired value by a certain small amount, movement of the controls takes place On-and-off control using simple globe or balanced-disc valves is simple and cheap, particularly where large valve sizes are required The on-and-off method of control is the one normally used in laboratory thermostats using electrical heating

The on-off method has an advantage in industrial practice in that by applying large changes of heat input to the furnace large temperature gradients are developed which speed up the flow of heat from the source to the contents

Two-position control is generally applied to processes where the heating or cooling rate is small compared with the thermal capacity of the system

(2) The proportional method

This type is also called " corresponding control " and " throttling control " the latter due to the definitely allocated band of values (termed the " throttling band') in which the mechanism acts This band may either be " narrow," say less than 10 per cent of the scale width, or " wide," in which case the band of proportional response may extend in some cases over the full scale-range of the instrument In the " on and off' system, small deviations of temperature cause the same movement of the controls as large deviations, and it would sometimes be more convenient, as in proportional control, to connect the position of the controls with the extent of the departure of the temperature from the set value This can be done fairly readily with air-operated controllers (*vide infra*) in which the air-flow is throttled by a varying amount, resulting in variation of pressure in the head of a diaphragm valve regulating the flow of fuel gas, or other heating medium The same principle of proportional control can, however, be used in mechanically operated controllers, which move the valve by an expanding solid or fluid medium, as well as in electrically-operated controllers, so that the term proportional is more apt

The proportional control system can be represented by the equation

$$\theta = \theta_0 - k_2 e$$

where θ denotes the valve position, k_2 the displacement of the valve from the normal position per unit of error, e the error or deviation from set-point, θ_0 the valve position which gave control under initial load conditions

The proportional band or throttling range is the range within the limits where the valve is fully open or fully closed Within this throttling range there is a fixed and proportional position of valve opening for each temperature The throttling range is adjustable, and each application requires an adjustment which must be established by trial A narrow throttling range causes a large change of heat input for a small departure of the temperature This will restore the temperature more quickly, but in doing so it has the same effect as on off

control and tends to overshoot and cycle badly. A wide throttling range does not restore the temperature quickly enough and tends to give larger errors with load change.

The correct throttling range is established by gradually decreasing the throttling range under proper load conditions until the temperature begins to cycle badly and then increasing it until the cycling amplitude is decreased to the proper value.

With proportional control a rather important effect occurs when the load changes. For example, if the system is controlling the temperature of water flowing through a tank by controlling a valve supplying steam to heat the water, and the flow of water through the tank is suddenly increased, then the steam input must also be increased. The steam valve opening at any time is dictated by the deviation of the water temperature from the required point at that time. The temperature, however, will not return fully to the required value, because as it begins to rise the valve begins to close again. The temperature will therefore remain at some value below the required temperature, and the only way in which the valve opening can be increased to provide for greater flow of steam is for the controller to settle out at the new temperature below the fixed point.

This deviation or depression from the control point is called the offset, load error or droop. It will be seen that the smaller the throttling zone the smaller will be the error of this type caused by changes in load, steam pressure, calorific value of the fuel or electric power voltage.

Principle of mechanism

The mechanisms* for air-operated proportional control systems generally take one of two forms. The pointer of the measuring system is connected to a flapper which restricts the flow of air from a jet and so sets up a back pressure of air which actuates a diaphragm valve (see Fig. 113). The back pressure is a function of the distance between the flapper and jet. A region of linearity exists of the order of 0·001 in. and various mechanisms are employed by manufacturers to increase the effective width of this region so as to obtain a proportional band of the required width.

A simple method of amplification is to connect the measuring system and flapper through a lever system, having a large and adjustable mechanical advantage, instead of directly together. A large movement of the pointer is thus required to move the flapper through its proportional band. In practice it is difficult to avoid lost motion by this system, due to slight play in the connecting linkages.

The other method of obtaining proportional control is to replace the flapper by a blade or vane, moved by the measuring system between two opposing

nozzles This latter system has the advantage of putting less loading on the flapper and hence on the movement of the measuring device (Fig 31)

To obtain amplification with this method a shaped vane may be used (see Fig 32) The arc of the vane is cut to have the same radius as the distance from the nozzle to the axis of rotation of the two pivoted nozzles

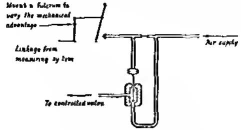

Fig 30 —Proportional control
Nozzle and flapper type

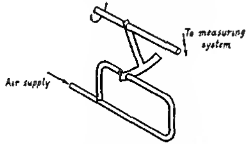

Fig 31 —Proportional control
Moving vane type

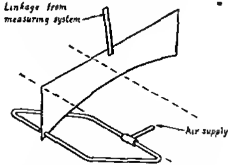

Fig 32 —Proportional control
Shaped vane and adjustable nozzle type

(3) The "floating" control method

The name "integrating" control is sometimes given to this classification In this system the controls are not placed in a position directly related to the

temperature, but are slowly moved, sometimes continuously, in one direction or the other, the rate of motion and its direction depending on the direction and extent of the deviation of the temperature from the desired value. The valve is thus kept slowly oscillating. If hunting is to be avoided and the valve stopped before it has reached the limit of its travel before the error has been corrected, the rate of motion of the control valve must be very slow. This is the main disadvantage of the "floating" method.

In another type of floating control with "high-off-low" contacts there is a definite inert space, or dead zone, between the two contacts, which further limits valve motion and avoids continuous hunting of the temperature.

Mathematically the proportional speed floating control system can be represented by the equation [1]

$$\frac{d\,\theta}{dt} = -k_1\,e$$

where t is the time that the system is away from the set point ; k_1 the rate of valve opening per unit error or deviation from the set point.

On integration this equation gives

$$\theta = \theta_0' - k_1 \int e\,dt$$

where θ_0' is the constant of integration and represents the initial valve position when the controlled variable was at the set temperature point.

From this equation it can be seen that the valve opening is proportional to the integral with respect to time of the deviation from the set-point, hence the term "integrated error control" for this form of control.

The advantage of floating control over proportional control is that it always brings the controlled variable back to the set-point, provided the load change is within the capacity of the controlled valve. Floating control is useful where load changes occur, provided these are slow changes.

Two-speed floating control, using two high and two low contacts, allows the rate of valve movement to be faster as the temperature departs farther from the control point.

Proportional plus floating control

The benefits of both the "proportional" and "floating" methods of control can be secured by using the proportional method as the basis of control, with the floating method to give a slow motion of the controls. The mechanism imposing the floating action on the proportional controllers is known as a "stabilizer."

The floating control in itself is not in common use, but as a component of more complex types, as that just indicated, it is quite important.

Other names for this duplex type are —"throttling plus-floating," "throttling plus-reset," "proportional reset," etc

A form of control closely allied to the simple two position class is what has once been termed the "two-position with rate" control, or what is more commonly called the "constant-speed floating" control As the term implies, it differs from the two position type in that it gives to the action of the controlling mechanism a definite rate when the temperature is on one side or the other of the control setting

In practice when combined with a proportional controller, the adjustment of the floating action is not critical, provided the floating rate is sufficiently slow to prevent it from causing hunting Higher floating rates may be employed in conjunction with proportional control without causing hunting, than with floating control alone

In a floating and proportional controller the valve movement is proportional to the combined effects of the floating and proportional methods, or expressed mathematically the valve position θ is proportional to the algebraic sum of the floating and proportional effects—

$$\theta = \theta_0 - k_1 \int e\,dt - k_2 e$$

Principle of mechanism

In proportional control systems a pressure is applied to the controlled valve which is proportional to the deviation of the temperature from the set point. If now this pressure is also fed through a restriction to a bellows whose elongation is opposed by a spring then the rate of increase of pressure in this bellows, and hence its rate of movement, is proportional to the deviation of the temperature from the set point (It is assumed that the total volume of the bellows is large compared with the increase in volume)

If the bellows is made to act on a pilot valve, or nozzle flapper assembly, a rate of change of valve movement, and hence a rate of change of valve position can be obtained which is proportional to the deviation of the temperature from the set point

The principle of applying a floating component to a proportional controller has been illustrated by Broadhurst and others [3] and is shown in Fig 33a

Assume that the air pressure applied to both the balance and proportioning controller is $2x$ lb /in², then the proportional controller is arranged to give an output of x lb /in² when at control point Then bellows A and D hold the arm in balance, since D has half the leverage of A At equilibrium the beam can remain in balance for any secondary pilot-valve pressure since B and C are at the same pressure and have equal moments If now a load change takes place and the pressure in A increases, the balance deflects and the secondary

pilot valve readjusts itself until the pressure in B equals that at A. This is only a transient state, however, since the pressure in B begins to leak through the needle valve into C so as to equalize the pressures in B and C. Therefore the secondary pilot moves to increase still further the pressure applied to the controlled valve and to B. Finally, when the system has settled to equilibrium at the new load, the value of the temperature is again at the set point, the pressure at A has returned to x lb., while the pressures in B and C are equal but at some higher pressure than that which they had before the load change.

With this arrangement the needle valve is the restrictor and C the bellows, which add to the valve movement the integrated error term. The value of the

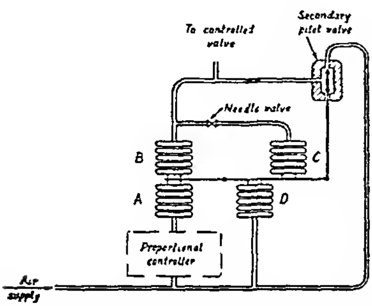

Fig. 33a.—Principle of floating component As applied to proportional control

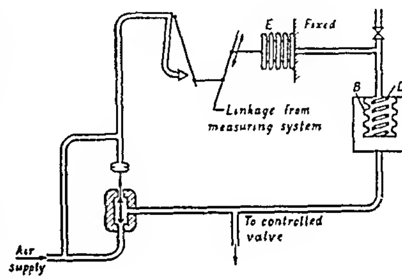

Fig. 33b.—A variation of the system illustrated in Fig. 33a

constant k_1 is varied to suit process conditions by varying the opening of the needle valve.

Different manufacturers use variations of the above principle such as that shown in Fig. 33b. Instead of feeding the proportional pressure through a restrictor into the floating component bellows, the proportional pressure is applied to a chamber B and so compresses a subsidiary bellows D connected to a further bellows E which acts back on the nozzle. The floating component is then added by the leak valve which allows the pressure in the subsidiary and last bellows to vent to atmosphere. Thus at equilibrium the pressure in these two bellows is atmospheric, although it may be above or below this pressure when load changes are occurring.

First Derivative Control

This control is a recent application and gives an opposing valve displacement proportional to the rate of change of the temperature from the set point. It cannot be used alone, since it would permit the temperature to balance out at any steady value. Expressed mathematically the valve position is proportional

to the first differential of the control error—

$$\theta = \frac{-k_3\, de}{dt}$$

where k_3 is the displacement of the valve per unit rate of change of error

PROPORTIONAL PLUS FLOATING PLUS FIRST DERIVATIVE CONTROL

Derivative control is incorporated with proportional plus floating control (see Fig 34) and assumes the simple expediency of delaying the action of the follow up of mechanism to some extent For if a process is subjected to wide load changes and considerable measuring lag, then proportional plus floating control may be unable to prevent considerable departure from the set temperature followed by either a very slow return to set temperature or a rapid return with considerable hunting

If a first derivative control is added then immediately e changes at a finite rate, corrective action is applied to reduce this rate Similar action of this term slows up return to the set temperature after a disturbance

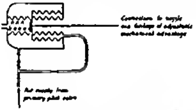

Fig 34—First derivative control
As applied to proportional plus floating control

As previously stated, in a floating and proportional controller the valve movement is proportional to the combined effects of the floating and proportional methods If the control error is positive, i e the meter reading is above the desired value, and is still rising, both the floating and proportional effects will cause the valve to move towards its low position, but if the control error is negative, i e the meter reading is below the desired value, but rising, the floating and proportional effects are in opposition, as the floating method will require the valve to travel towards its high position, since the meter is registering below the desired value, but the proportional method will lower the valve position as the meter rises

In a floating, proportional and first derivative controller the valve movement is proportional to the sum of all three effects—

$$\theta = \theta_0 - k_1 \int e\, dt - k_2 e - k_3 \frac{d\theta}{dt}$$

The damping action is utilized by adjusting k_1 and k_2 so that acting alone

they would produce a rapid return, although with subsequent excessive hunting. The addition of the k_3 term damps this hunting.

If excessive first derivative component is used the system will approach the set temperature too slowly after a load change, if insufficient is applied overshooting will result.

In conclusion it may be stated that though the most advanced method of automatic control in industry at the moment is one employing proportional, plus floating plus first derivative, all industrial automatic control problems do not require this system.

A plant that has one major lag (known as first order lag) is easy to control by the proportional or floating and proportional methods, and no improvement will result if the first-derivative method is added. A plant with two lags in series, whilst more difficult to control, can still be dealt with satisfactorily by these methods.

Plants with three or four lags in series are still more difficult to control and can be improved by the addition of the first-derivative function. Some temperature control problems are of such nature.

The response of the meter reading to a movement of the control valve is very slow at first and then accelerates before finally steadying out.

If one of the lags happens to be large in comparison with the remainder, its effect will partly swamp the remaining lags, making the control problem easier than it would be if all the lags were of similar value.

Reference

(1) BROADHURST, BRODERICK, FOSTER AND WHEELDON, *Inst. of Elec. Eng. Convention on Automatic Regulators and Servo- mechanisms*, May, 1947.

CHAPTER 8

Industrial types of regulators based on the expansion of a liquid

REGULATORS of the liquid-expansion class have found extensive application for the heat control of industrial furnaces and boilers, and for domestic purposes Instruments of this group can be divided into two types—

(1) Self-operated

(2) Air-, steam- or water-operated

The latter are by far the most commonly used industrially

Principle of operation of self-operated controllers

The sensitive bulb in the instruments of this first class is connected directly or by capillary tubing to a pressure-responsive element adapted to operate a valve or electrical contacts Adjustment of the control temperature is usually made by regulating the pressure of a spring or arrangement of lever and weight which opposes the actuating pressure The force available to close a valve is small, so that there is a risk of incomplete " shut-off," which may result in a slow rise of temperature, with consequent damage to the instrument itself

It is almost invariably necessary to have a large sensitive bulb when the pressure-responsive element is a bellows operating a valve, and this gives rise to difficulty in installation, apart from a disadvantageous time lag in heat transfer to the sensitive bulb and contents

The sensitive element may contain liquid of the volatile type, or of a non-volatile type like mercury, or even a gas-filled element may be used When the volatile-liquid type is used, the flexible tube connecting the bulb to the valve-actuating bellows should extend down on the inside of the regulator bulb so that its end shall always be immersed below the surface of the thermo-sensitive liquid, thereby constituting a "trapped-vapour" construction preventing any of the vapour formed in the bulb from passing over to the bellows, and ensuring that the power shall be transmitted entirely by liquid pressure If this were not so, and any vapour were allowed to pass over into the bellows, this vapour would condense in the cooled bellows and no pressure could be built up until sufficient liquid had distilled over into the bellows to fill them On the reverse operation, it would be necessary for all the liquid in the bellows to be redistilled back into the bulb

In cases where it is inconvenient to place a sensitive bulb in the tank of a machine, it may be possible to incorporate the sensitive element in the pipe-lines. A suitable pipe, through which the liquid to be controlled circulates, is made double-walled for a certain length. The inner tube may be plain or corrugated. The space between the two walls is filled with a volatile liquid and hermetically sealed, except for a connection by means of a capillary tube to the control valve. With this form of instrument the ratio of exposed surface to volume of the sensitive medium can be made very great. For pasteurizers for milk, cider and fruit-juices, which are heated whilst in circulation, this form is particularly convenient.

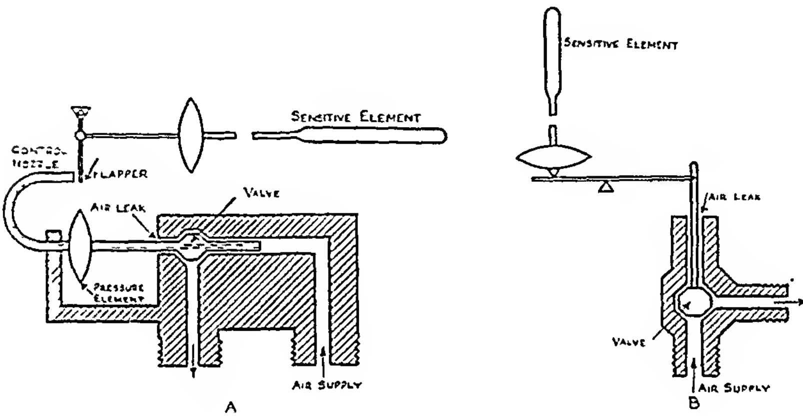

Fig. 35.—Pilot valves for air-operated controller
(A) Reverse-acting (B) Direct-acting

The danger of breakage and the mixing of the volatile liquid with the contents of the pipe is present, but with careful construction this danger should not be greater than with the use of a bulb in the usual way.

Principle of operation of air-, steam- or water-operated controllers

These make use of a pilot valve, controlled by the expansion of a volatile or non-volatile liquid contained in a bulb inserted in the heated space. The pilot valve then regulates the pressure of air upon the diaphragm or bellows of the main control valve. Where large valves or slides have to be operated, the pilot valve controls the direction of air, water or oil flow to a power cylinder capable of developing up to about 5,000 ft-lb per stroke.

The pilot valve takes one of the two forms shown in Fig. 35. In the form (A), expansion of the sensitive element, on rise of temperature, causes a flapper

to close or partially close a nozzle from which air is issuing This raises the pressure in the pressure element, causing it to expand and close the pilot valve, whereby the air leak is opened and the air cut off from the diaphragm valve This latter valve is so arranged that reduction of pressure causes it to close and cut off the heating medium When the flapper uncovers the nozzle, with fall in the controlled temperature, the air leak is closed and air pressure applied to the valve In the form (B), movement of the expansion element controls the pilot valve directly Rise in temperature causes air pressure to be applied to the main valve to close it

There are a number of variations of the foregoing principle The opposite effect in either (A) or (B) is obtained by changing the position of the pilot valve so that rising temperature affects the main valve in the reverse manner The main valves used in conjunction with these regulators may either be direct or reverse acting, and are referred to in the Appendix

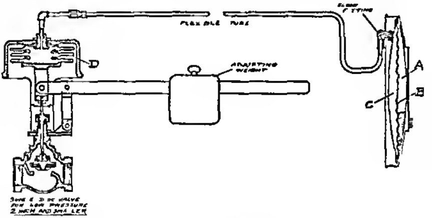

Fig 36 —The Powers regulator

SELF-OPERATED TYPES

One of this type of regulator manufactured by the Powers Regulator Company consists (Fig 36) of two compartments, *A* and *C*, divided by a flexible corrugated bronze diaphragm *B* One compartment contains the volatile liquid, the expansion of which forces the metal diaphragm back and expels air out of the rear compartment through a flexible connecting tube and into a bellows *D* operating the control valve of the heating medium When the temperature falls, and the pressure decreases, the gas valve is opened again by means of a lever and weight The pressure in the bellows is directly proportional to the temperature of the compartments , consequently the position of the adjusting weight on the lever will determine the temperature at which

the valve will close, and the operation being gradual, the passage afforded by the valve opening is proportional to the temperature. By changing the positions of the adjusting weight, different temperatures over a 20° F or 10° C range are secured. Such a thermostat for house-heating purposes has a sensitive element in the form of a capsule about 12 inches in diameter and $1\frac{1}{2}$ inches in depth, enclosed in an open-pattern cover fixed on the wall of the room where atmospheric temperature control is required. The flexible connecting tube may be of any length up to 75 feet, or with smaller valves 100 feet, and is usually of lead armoured with galvanized steel wire. Armoured copper tube is employed where conditions such as excessive vibration require its use. For the control of draught dampers on a heater, the valve is omitted and the bellows are enclosed in a housing with a suitable supporting flange, connection being made by means of chains between the end of the lever and the heater dampers.

The Morgan Crucible Company manufacture a thermostat which whilst strictly not being a self-operated type, does open and close contacts directly, to operate relays. This instrument is based on the principle that, for comfortable conditions in a room, the heat loss from an object at a temperature corresponding somewhat arbitrarily to that of a human being should be a constant quantity. The instrument consists essentially of a hollow blackened copper sphere about 5 inches in diameter ; this sphere, an illustration of which is given (Fig. 37), is mounted on a cylindrical sump, which is housed inside the base. The sump is filled with a volatile liquid and contains a small heating coil as well as a bellows diaphragm, the movement of which causes contacts in the circuit of the master relay controlling the heating apparatus to be opened or closed. The heating coil is loaded continuously at from 4 to 8 watts, so that the liquid is evaporated at a constant rate and rises into the sphere, where it condenses on the inner surface of the copper and drains back into the sump. The rate at which this condensation takes place, and therefore the vapour tension inside the sphere, obviously depend on the rate of heat flow through the copper walls. If this rate of flow is, say, increased, owing to a change in the conditions in the room, the temperature of the sphere will drop, the rate of condensation will increase, and the vapour tension will fall. The bellows diaphragm, one side of which is exposed to the atmosphere, will therefore expand and close the relay contacts, so that the relay will operate and the heating apparatus be switched on.

The relay (Fig. 38) consists of a vertical glass tube, from which a horizontal arm projects, carrying two contacts. A quantity of mercury, on which an iron rod floats, is sealed into the tube. The lower part of the latter is surrounded by a solenoid, one end of which is connected to the mains and the other to one of the contacts in the sump. The other contact in the sump is also connected to the mains. When these contacts are closed, the solenoid is energized, the

iron rod is drawn downwards and the level of the mercury is raised so that some of it flows into the horizontal arm completing the circuit between the two

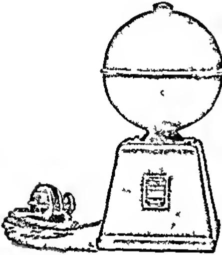

Fig 37—Radiation thermostat for room temperature control

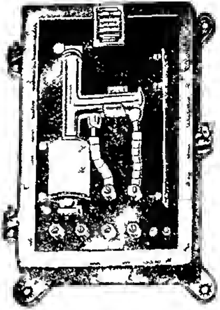

Fig 38 Control relay for radiation thermostat

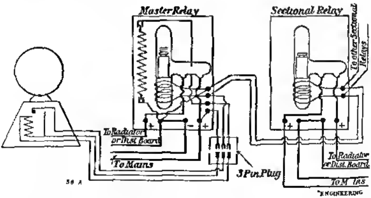

Fig 39—Diagram of connections of operating relays for radiation thermostat

contacts therein As will be seen (Fig 39) these contacts are in the radiator circuit so that the heating apparatus is switched on

Bearing thermostats

It is desirable to have an automatic means of stopping an unattended machine before damage is done, in the event of its bearing becoming overheated. The sensitive element, usually a bulb containing a volatile liquid, is embedded in the bearing itself or placed in the circulating oil if this is possible. Attainment of a dangerous temperature causes a switch to be tripped. The liquid

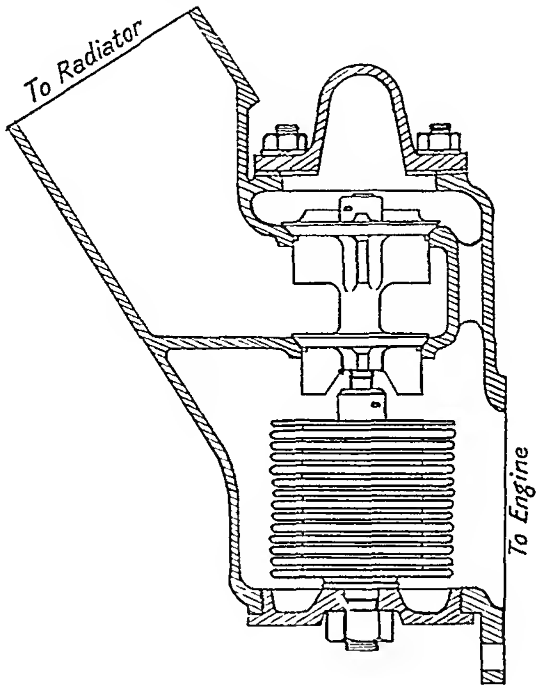

Fig. 40.—Car thermostat: bellows type

is generally contained in a brass tube and moves a piston which throws off a quick make-and-break switch. The switch is held in the off position until re-set by hand, and is normally capable of carrying power from the mains. Adjustment is usually provided for the switch to open at from 60° C to 90° C.

Liquid-expansion thermostat for motor-car engines

Motor-car engines usually have their carburettors set so as to give their maximum power with the highest economy when the water-jacket temperature is about 180° F, and there is a lack of efficiency until this temperature is attained.

It is desirable therefore to prevent the cooling of the circulating water by passage through the radiator until this temperature has been reached Alternatively the thermostat may operate radiator shutters The temperature should be maintained regardless of weather, load or road conditions

A common form of thermostat for this purpose consists of metal bellows containing a volatile liquid The bellows are made so as to be fully extended before the liquid is put in but when filled and sealed up are in a state of compression due to the internal pressure being below that of the atmosphere The bellows are inserted in the cooling water at a point between the top of the cylinders and the radiator and when the pre determined temperature is reached the liquid vaporizes and expands the bellows To the bellows is connected a valve controlling the rate of flow of the water into the radiator The flow of water from the cylinders to the radiator cannot commence until the water around the cylinders has attained a temperature of at least 140° F when the expansion of the bellows opens the valve slightly As the expansion increases with the rise in temperature the valve continues to open proportionately until a temperature of about 170° F is reached when all the cooling water is in full circulation Should the bellows be punctured accidentally they would fully expand giving an unrestricted water flow

This thermostat may be used in one of two ways either to obstruct the flow of hot water from the cylinders to the radiator or to by pass the water from the cylinder block back to the bottom of the radiator or pump The first alternative is shown in Fig 40 Guiding vanes for the valves are generally used to prevent them sticking and a small hole of about $\frac{1}{8}$ inch diameter is drilled in each valve to prevent the formation of air locks The valve diameter is so chosen that when the valve is fully open the flow area uncovered is equal to that of the main water pipe In cases where this diameter cannot con veniently be made large enough two valves in parallel are used as illustrated in Fig 40

Other types of control such as those embodying a bimetallic strip are employed for the same purpose and these are described in another chapter

AIR-OPERATED TYPES

Capsule operated control

The *Tycos* temperature regulator which is of the air operated type is illustrated in Fig 41 and details of the air valve are shown in Fig 42 The sensitive bulb is connected by means of flexible capillary tubing with a small metal capsular chamber 8 (Fig 41) within the case of the instrument When the capsule expands sufficiently the valve stem is raised so as to allow a free passage to the compressed air through the regulator to a diaphragm valve

This air inflates the diaphragm of the valve, causing the valve to shut off just enough heating medium to maintain the temperature at the desired point. An air-leak 5 allows the air to be exhausted from the diaphragm when the temperature falls. Adjustment for temperature is made by the rotation of an

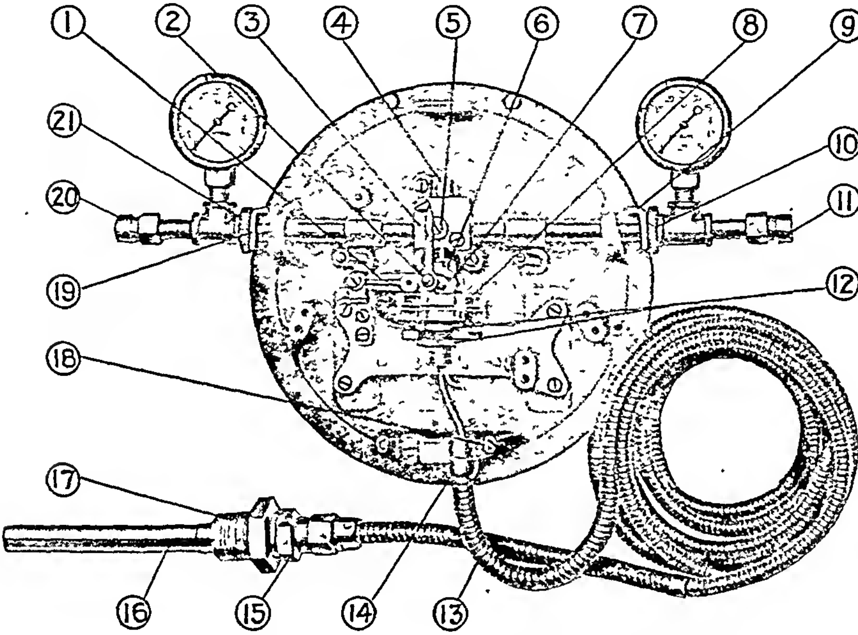

Fig. 41.—Tycos "Singl-Duty" air-operated temperature regulator

(1) Rocker-arm and bracket for cam (7).
(2) Cam-adjusting key-post.
(3) Air-valve block.
(4) Air-valve cap
(5) Adjustable air-leak
(6) Rocker-arm stud which engages air-valve plunger
(7) Temperature-adjusting cam.
(8) Capsular chamber.
(9) Front case clamp plate.
(10) Front case lock-nut.
(11) Air inlet (union butt).
(12) Capsular chamber lock-nut.
(13) Bronze-armoured connecting tubing.
(14) Ferrule
(15) Swivel nut.
(16) Bulb.
(17) Union connection hub
(18) Ferrule set-screw
(19) Front case clamp plate.
(20) Air connection to diaphragm valve.
(21) Front case lock-nut.

eccentric cam 7 in the form of a disc, which is interposed between the capsule and the valve stem.

Reverse-acting regulators are of a similar design to the foregoing, except that the air valve closes when the temperature rises above, and opens when it falls below, the desired value.

For the control of two heating media—or one heating and one cooling medium—to maintain a constant temperature, one bulb is used which is divided into two compartments, each compartment being connected to its individual capsular chamber in the instrument case Each capsule controls two separate valves One capsular chamber is direct acting, and regulates the valve in the steam line, while the other is reverse-acting to regulate the water-line valve A single adjustment device controls both sides, after each side has been set separately

The primary reason for manufacturing a control for use with two heating media—exhaust steam and live steam—is because the supply of exhaust steam

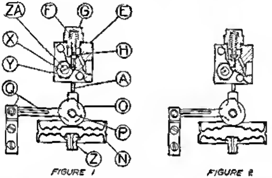

Fig 42 —Diagram showing operation of Singl-Duty direct action air valve block

(1) Capsular chamber in normal position and air valve closed
(2) Capsular chamber in inflated position and air valve open
(A) Lower valve plunger
(E) Air valve block
(F) Valve spring
(G) Air valve cap
(H) Upper valve stem
(N) Capsular chamber
(O) Adjusting cam
(P) Adjusting key post
(Q) Rocker arm and bracket
(X) Air leak screw
(Y) lock nut
(Z) Capsular chamber fitting
(ZA) Air leak

is liable to fail With this device as soon as the temperature falls below a certain limit, due to failure of the exhaust steam supply, and it becomes necessary to resort to live steam, the regulator closes the diaphragm valve in the exhaust steam discharge line and opens the diaphragm valve in the live steam line

Air pressure of 25 lb per square inch is employed with the foregoing types of instruments, but pressures as high as 40 lb can be used

Jet type of control

An example of the jet and flapper type of control is shown in Fig 43 Ranges of temperature can be selected from (1) a vapour pressure type of

sensitive element covering $-80°$ to $500°$ F; (ii) a gas filled type for $-60°$ to $1{,}000°$ F, and (iii) a liquid filled type for $-60°$ to $212°$ F, or equivalent Centigrade values.

Sensitivity.—The sensitivity of the instrument is adjustable by moving the support of the spring-strip flapper away from the nozzle to increase the

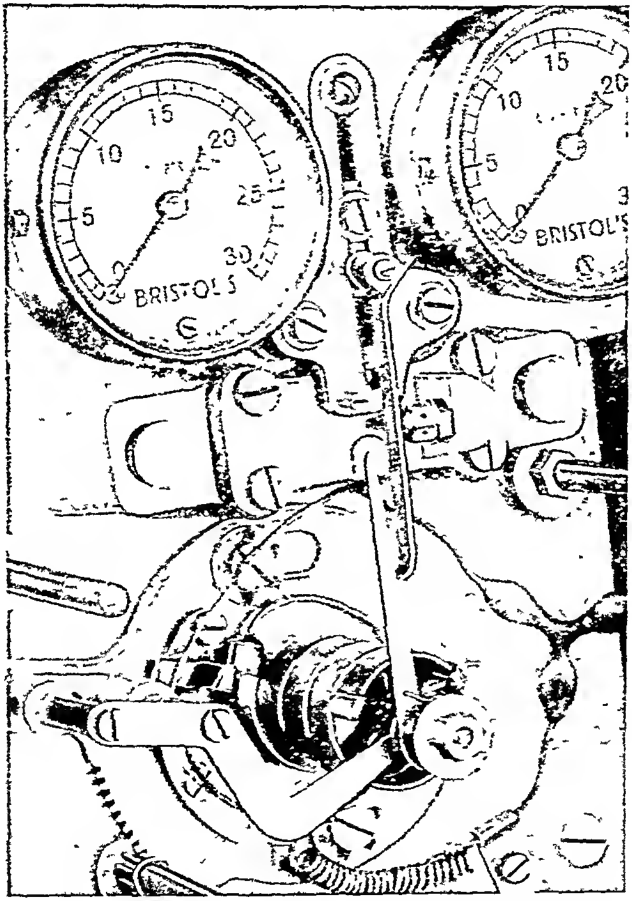

Fig. 43.—Bristol's jet and flapper type of control instrument

sensitivity or towards the nozzle to decrease sensitivity. The throttling range is thus adjustable to suit the process.

Direct and reverse action.—By changing the position of the flapper and jet assembly to the other side of the actuating lever attached to the Bourdon tube

it is possible to change from direct to reverse acting This can be done simply with the aid of a screw driver

Moving vane type

An example of the moving vane type is the *Bristol Free vane Air operated Controller*, illustrated in Fig 44 The actuating element 9 through connection

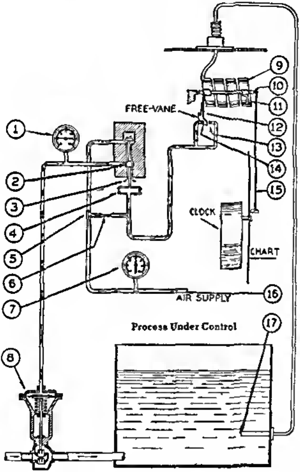

Fig 44 —Bristol's free-vane air-operated controller

11 rotates the shaft 10 to which the recording pen arm (not shown) is attached A thin vane 12 is also attached to this shaft, and as the shaft rotates in response to changes in temperature, this vane passes between two nozzles 13 and 14, which are discharging opposing jets of air, and in so doing throttles the discharge of air It is by means of this throttling that control is effected

Air at 15-lb pressure is admitted at 16. Its pressure is shown on the gauge 7, and a branch leading off to the left supplies air to the orifice 6 and pilot valve 2. The object of the orifice is to restrict the flow so that only a limited amount of air can pass through to the diaphragm 4 and the nozzles 13 and 14. These nozzles are so proportioned in relation to the orifice 6 that when their discharge is not throttled they permit enough air to escape so that only a slight pressure is produced in the diaphragm 4. As the edge of the vane cuts into the discharging jets of air, as already stated, the discharge from the nozzles is throttled, the amount of throttling depending upon the position of the vane. When the vane cuts entirely through the jets of air the throttling is at a maximum, and a much higher pressure is built up in the diaphragm 4. The function of the diaphragm is to operate the pilot valve 2. Full air-supply pressure is always maintained over the top of the pilot valve, and when the diaphragm opens this valve, air is allowed to flow to the diaphragm motor valve 8, the gauge 1 showing the amount of this pressure. A small amount of air is permitted to leak out through the adjustable bleeder 3. When the pilot valve passes more air than the bleeder can discharge, the pressure increases at the diaphragm motor valve. When the pilot valve passes the same amount of air as the bleeder discharges, the air pressure remains constant on the main diaphragm valve. Since the opening of the diaphragm valve depends upon the air pressure to which this valve is subjected, it follows that this opening is determined by the movement of the vane 12.

The two opposing nozzles 13 and 14 are separated by a distance which is approximately one-fourth the diameter of the jets. This arrangement conserves air, as the two jets discharge no more air than does a single jet. It also serves to balance the vane. The vane, being thin and flexible, assumes a position midway between the two nozzles and substantially reduces the discharge of air without coming in actual contact with either nozzle, literally being " floated " by the two jets of air. In this way friction on the vane is minimized.

The vane can readily be rotated about the shaft and locked in any position desired. This adjustment is utilized to convert a direct-acting valve into a reverse-acting valve, or vice-versa.

The free vane controller is a proportional controller with a fixed throttling range, normally of approximately 2 per cent of the scale.

Shaped vane type of Proportional Controller.—In order to obtain greater amplification than is possible with the simple vane type a shaped vane may be employed. An example of this form is illustrated by the Ampliset Free Vane Controller shown in Fig. 45.

In principle the throttling range of the controller is changed by rotating the jet arm L about its axis in such a manner that a different portion of the curved edge of the vane C passes between the jets L to obtain control. With the jets L set to operate on the outer edge of the vane C the vane has its greatest

linear motion per unit deflection of the measuring system With the jets set at the outer edge of the vane *C*, as shown in Fig 45, the controller has a narrow throttling range or high sensitivity, because a relatively small deflection of the measuring system causes the vane to move a considerable distance across the face of the jet openings, and thus a relatively small change in the conditions

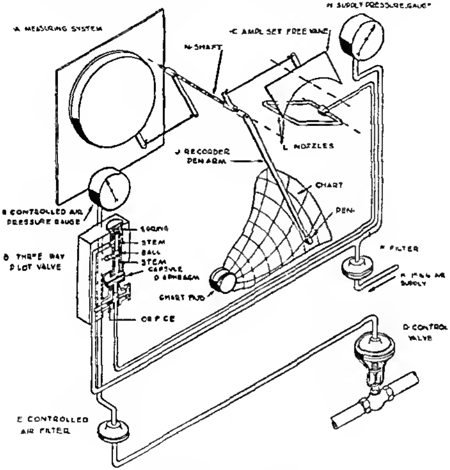

Fig 45 —Shaped vane contro
Bristol s Ampliset controller

under control will cause a maximum change in the setting of the control valve *D*

When the jets *L* are rotated away from the outer edge of the vane to a point nearer its centre the extent of the linear motion of the vane across the nozzles is less for the same deflection of the element With the jets in this new

position the controller has a wider throttling range and a lower sensitivity, because a great change in the medium under control is required to produce a given linear motion of the vane between the jets than is produced with the jets in a position farther from the centre of the vane *C*.

By manual adjustment of the jets on the arc of the vane *C*, the sensitivity of the controller may be changed on the job to take care of time lag. By the same adjustment the instrument may be changed from direct to reverse acting and vice-versa.

This type of controller is suitable for processes where the time lag is not great and the load or demand for fluid through the control valve changes only a moderate amount in maintaining constant results.

The *Kent Proportional Controller* has some interesting features. Fig. 46 illustrates diagrammatically the action of this controller. As pressure, flow and liquid controllers have a similar mechanism to the temperature-controller, the mercury-chamber float represents diagrammatically the sensitive element of the temperature-control.

Air pressure is supplied to the delivery jet *B* and is controlled by the pilot-valve vane *A* whose movements vary the pressure received by the jet *B* in the line *P*. This pressure is then transmitted to the diaphragm chamber, thus compressing the springs of the valve, which alters the flow of heating medium.

The value at which the controller is to maintain the controlled quantity is indicated by the pointer *C*, which moves over the diagram or chart concentrically with the pen *D*. A manual setting dial *E* is provided for setting the pointer.

Pivoted to the combined pointer and crank *C–G* is the differential link *H*. This link is slotted at the lower end so as to ride on the pin *J* which is fixed in *F*. Thus the centre-line lies across the pivoting centre of *F* and *G*, when the set value and the actual controlled value coincide. The connecting link *K* is attached to the differential link *H* by a shouldered pivot screw, so that for any deviation of *C* or *D* a movement is transmitted to the driving pin *Z*, which in turn moves the ratio arm *Q*, and the vane *A*.

The amount of movement transmitted to the vane *A* is proportional to the deviation of *C* and *D* from one another, and the setting of ratio arm *Q*. The latter is called the "sensitivity adjustment" and is accomplished by the setting dial *S*, which alters the position of the fulcrum and ratio arm *Q* relative to the position of the pins *Z* and *Y*.

A vane coincidence arrangement with setting dial *L* is also shown, and this, through an eccentric bush, alters the position of the vane relative to the nozzles in a horizontal direction, thus effecting a simple adjustment to bring the pen coincident with the setting pointer.

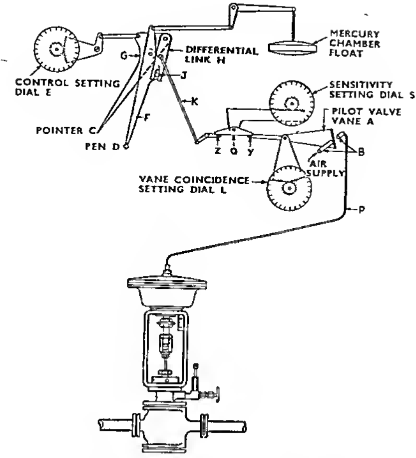

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Fig 46—Layout of Kent Proportional Controller

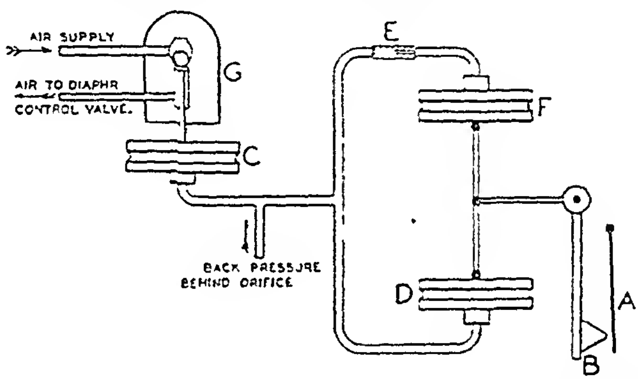
Stabilization of air-operated controllers

In order to eliminate "hunting" or "cycling," it is necessary to adjust the throttling range of the controlling instrument, or in other words its sensitivity, by way of compensation Stabilization by varying the throttling range is insufficient in some cases, and an additional system of stabilization is needed This usually takes the form of damping the initial movement

A common method is to employ two air capsules in opposition, interposed between the pilot valve and the diaphragm of the control valve These capsules are connected by a link to the orifice of the controlled air leaks, so that the orifice is moved in the required direction to counteract the first movement set up by the change in heat demand The control is therefore stabilized by causing

it to strike a balance between the two opposing tendencies and to determine a control-valve position which will supply the amount of correction required to maintain the temperature constant. As the action of this stabilizing element is always in proportion to the speed and magnitude of the change in heat demand, because it is governed by the initial velocity of the air flow through the relay system via the air-leak, good control is secured. There is little swing from the control point.

With one type of instrument, the air flow to one capsule is free and to the other restricted by the inclusion of a long length of fine-bore resistance tubing. In another, the air flow to the second capsule is controlled by an adjustable needle-valve. Other constructions are used, but the underlying principle is the same, and is that of controlling the back pressure on the pilot valve so that any new pressure applied to the fuel control-valve is gradually changed at a rate which is a direct function of the rate of change of the process temperature,



(Electro Meters, Ltd

Fig. 47.—Diagram showing one type of stabilizing system employed in air-operated temperature-controllers

bringing the temperature back on a curve which is tangential to the control-point, instead of cutting across it. (See Chap. 7.)

The system of stabilization described is illustrated by the diagram (Fig. 47). As the control-point is reached, the valve *A* commences to restrict the flow of air from the orifice *B*. Pressure is built up behind the orifice, causing inflation of the capsules *C* and *D*. *C* tends to open the pilot valve *G*, but *D* causes the orifice to move away from the valve *A*, thus permitting air to escape and release the pressure behind the orifice *B*. Meanwhile the trend of conditions needs correction, and the valve *A* continues to move towards the orifice *B* and repeats the above. At the same time, air is passing through the restriction *E* and inflating the capsule *F* at a slower rate than capsule *D*. Eventually *F* and *D* balance each other and the orifice is brought to its original position,

the pilot valve G is opened, and the control valve adjusted The action of the capsule F is to stabilize or damp the operation of the controller

Proportional plus floating controllers are frequently referred to by manufacturers as proportional controllers with automatic re set but the term re set

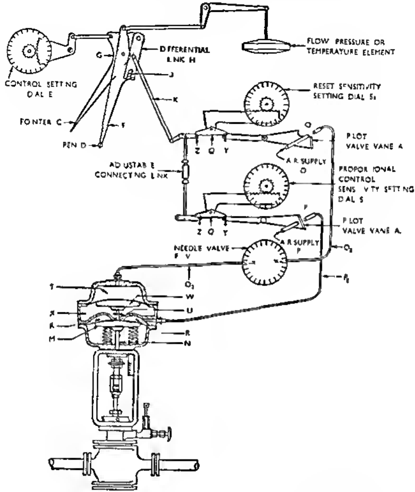


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Fig 48 —Layout of Kent proportional and re set controller

in this connection tends to cause confusion in terminology Nevertheless the term is used in this book to distinguish the manufacturers instrument

Fig 48 shows the controls of one form of Kent proportional plus floating controller The connecting link moves both ratio arms Q_1 and Q which are inter connected by an adjustable link Each vane has a sensitivity adjustment

The diaphragm valve is equipped with two diaphragms, and operating mushrooms which are mechanically tied together, but the pressure chamber of each is quite separate, one being filled and exhausted by pilot-valve A_1 through the needle-valve *FV* and known as the re-setting control, and the other by the pilot-valve *A*, the proportional control. The mushroom *W*, depressed by the pressure from the re-setting pilot-valve (into the chamber *T*), pushes down its spindle through the gland *U* and thus the mushroom *M* and spindle *N* which are directly connected to the valve. (The gland *U* prevents the pressure leaking upwards into chamber *X*, as the latter is in connection with the atmosphere.)

It will be appreciated that either of the mushrooms *M* or *W* can move the valve over its entire range. Normally, if proportional control only were used, pilot-valve *A* would send its pressure-variations via pipe P_2 to the space *R* above mushroom *M*, thus exerting an effort on this mushroom alone.

When re-setting control is used, the needle-valve *FV* is opened slightly, which allows pressure-variations from the high-sensitivity pilot valve A_1 to be communicated to the mushroom *W* via the space *T*.

As the two pilot-valves *A* and A_1 are tied together mechanically by means of the adjustable connecting link, it will be realised that for a small deviation a large potential pressure-change is caused by pilot-valve vane A_1 and a small one by pilot-valve vane *A*. Whereas *A* is in direct communication with mushroom *M* via space *R*, and moves it immediately, the larger effect of vane A_1 is delayed by the throttling of the needle-valve *FV*. If the needle-valve in line O_2 were closed completely, the controller would operate as a proportional controller, and thus the sensitivity of the pilot valve *A* would be determined by plant conditions. (It would be increased in sensitivity until the plant just failed to " hunt.") In some bad locations it will be appreciated that this would mean an undesirably large throttling zone.

Bristol proportional-plus floating control

The basic principle of operation of the so-called re-set free vane (Fig. 49) is that the movement of the free vane is governed, not only by the measuring element 2, but also by the diaphragm spring 11 connected through the differential mechanism 8.

On a clockwise movement of the element 2, the free vane is rotated into the back pressure of the jet system, expanding the capsule 5, which moves the pilot valve 4 to the closed position, decreasing the controlled air pressure on the diaphragm of valve 6. This decrease in pressure is transmitted through connection 3 to the bellows unit 13. This permits an internal spring to distend the bellows causing a partial vacuum in the diaphragm spring 11 which is compressed. This movement is transmitted through arm 10 and shaft 9 to the differential mechanism 8, resulting in a movement to the free vane of

opposite sense to that applied by element 2 this movement being subsequently withdrawn by dissipation through re set valve 12

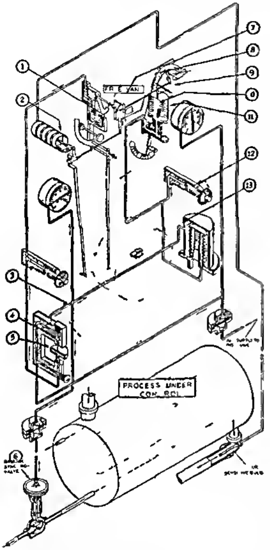

Fig 49 —Re set free vane controller
Diagram of Bristol s instrument

From this it will be seen that the measuring element 2 must move a greater distance from the control point to produce a given effect on the control valve 6 than would be necessary without the diaphragm spring assembly

In operation the procedure is continuous and follows changes in the value under control The throttling range being normally very narrow but temporarily widened in proportion to the rate of change and subsequently restored to its narrow value Corresponding action is produced by the measuring element moving in a counter clockwise direction

Kent Controller Mark 20

A Kent controller Mark 20 mechanism is available in a variety of forms which enable the controller to perform the following various functions proportional control only floating plus proportional proportional plus first derivative or floating plus proportional plus first derivative

The controller (Figs 50-52) incorporates a differential mechanism in the form of two U shaped members shown in the diagrammatic sketch Fig 50 at A and B Member A is pivoted to the framework of the mechanism mid way along its length and its right hand extremity is connected

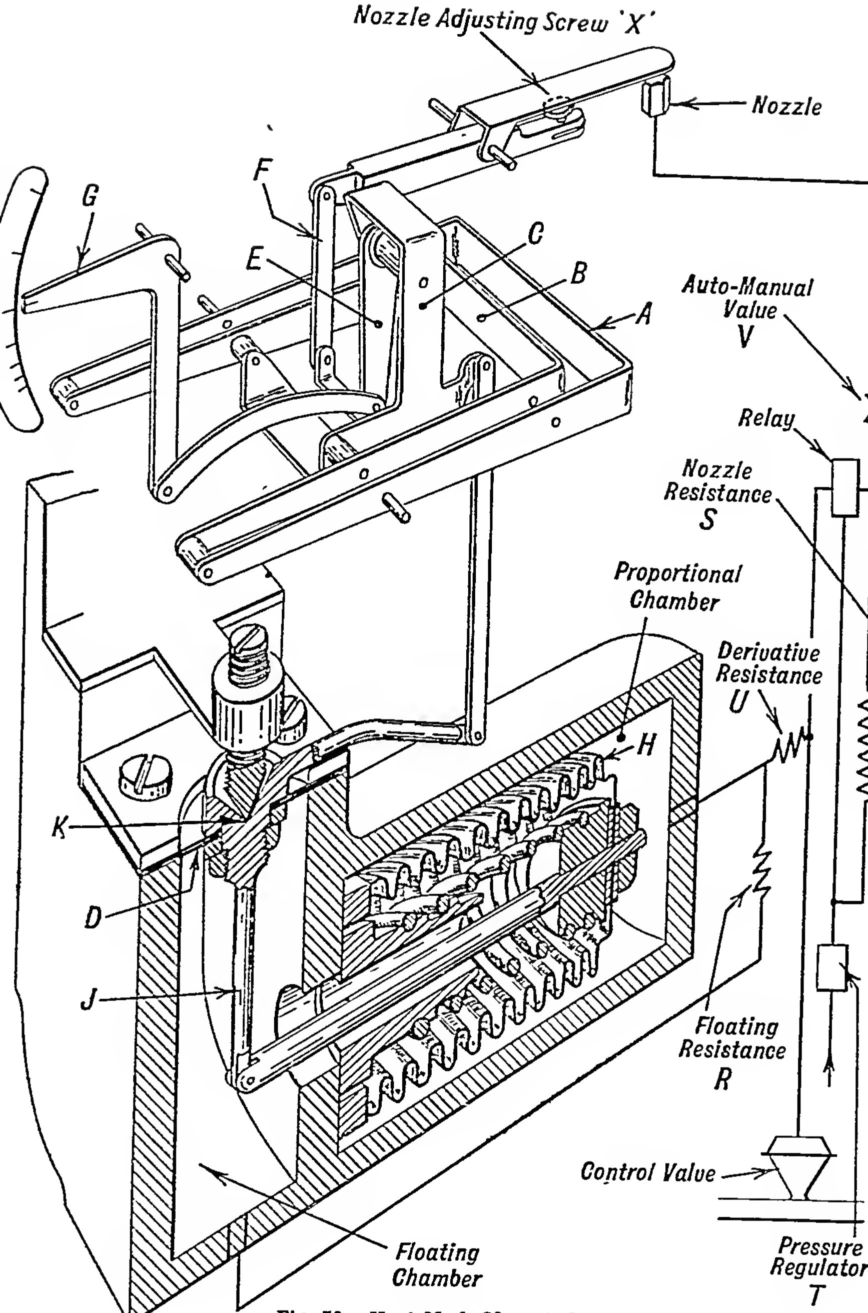

Fig. 50.—Kent Mark 20 controller

through suitable linkwork to the setting pointer of the measuring instrument Member B is pivoted to member A at their left hand extremities and is connected to the measuring instrument s pointer through suitable linkwork which is attached to the right hand extremity of member B Member B is also provided with two pivot holes mid way along its length arranged so that when measuring pointer and setting pointer are coincident these pivot holes are exactly opposite the pivot point of member A irrespective of the position of the measuring and set pointers positions on their scale If the two pointers

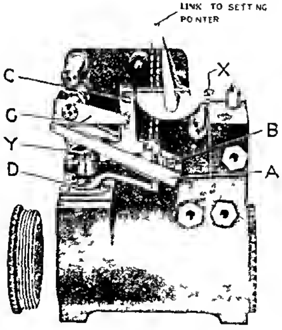

Fig 51 Kent Mark 20 controller

separate however the pivot holes in the centre member B rise or fall an amount proportional to the separation of the pointers The setting pointer can be set to any desired value on the scale with the control setting knob In some applications however the setting knob may be incorporated in the controller mechanism and directly geared to member A in which case the setting pointer is driven through the inter connecting linkwork

The central pivot holes in member B carry the left hand extremity of an inverted tee shaped frame C (Figs 50 and 51) which is in effect a floating differential link The right hand end of this frame is connected through a link

to one arm of a bell crank *J*, whose position is dependent upon the difference in pressure existing either side of a bellows *H* contained in a chamber forming the lower body portion of the frame work. The upper portion of the tee-shaped frame carries a pivot on which a lever *E* (Fig. 50) is attached, the lower end of which describes an arc which passes through the central pivot points of member *B* and the pivot of the interconnecting link to the bell crank *J* at the opposite end of the tee frame. Link *F* (Fig. 50) is attached to the lower end of the lever *E*, and conveys movement to the nozzle lever assembly mounted above. The angular position of the lever *E* is adjustable by the throttling range adjuster *G*, which enables its lower pivot point to be set in any position varying from (1) in line with pivot point of member *B* to (2) a point almost coincident with the bellows link attachment.

It will be seen that if the differential members *A* and *B* are displaced so as to cause the left-hand end of the inverted tee-shaped frame to fall, it will initially cause the nozzle link to rotate tbe nozzle lever about its fulcrum in an anti-clockwise direction, allowing air to escape from the nozzle, with a resulting reduction in air pressure behind the nozzle. The nozzle air pressure acts on the primary side of the relay, the secondary side of which transmits a similar pressure to the proportional side of the bellows and to the control valve. This allows the bellows to expand and causes the bell crank *J* passing through the diaphragm *D* to rotate about its centre fulcrum *K* in an anti-clockwise direction. The right-hand extremity of the inverted tee-shaped frame *C* is raised until the flapper is again brought into engagement with the nozzle, but a lower air pressure now exists in the proportional chamber and the control valve.

The amount the air pressure changes for a given displacement of the differential members *A* and *B* depends upon the position in which the lower pivot point of the nozzle link *F* is located along the base of the tee frame. For instance, if it were in the middle, i,e., link vertical as shown in Fig. 50, the amount of movement resulting at the right-hand extremity would be equal to the displacement at the centre of the *U* members *A* and *B*.

The floating control function is obtained by allowing the air in the proportional side of the bellows chamber to leak through a suitable adjustable needle valve resistance to the other side of the bellows, and so permit the control pressure to continue to rise or fall if the *U* members are separate, i.e., if the instrument is off its control point. The rate at which the control pressure varies for a given displacement of the *U* frame depends upon the value of the floating throttling resistance, and is proportional to the control error or separation of the two pointers.

When derivative function is required, an additional throttling resistance is included in the connection between the relay and the proportional chamber, so that the " follow up " effect of the bellows is delayed, and the pressure at

the relay secondary and control valve will be greater than that existing in the proportional chambers while the error or deviation from the control point

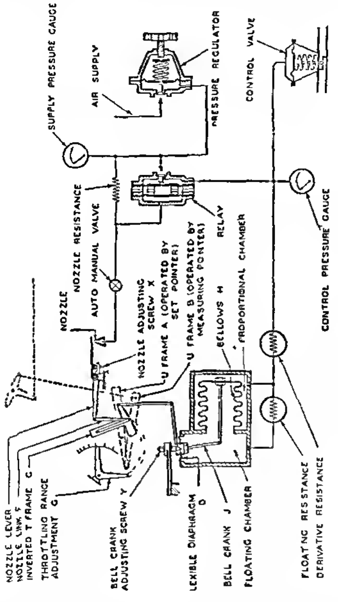

Fig 52 – Relay unit of Kent Mark 20 controller

is changing, due to the pressure drop across the aforementioned resistance, this value is dependent upon the *rate* at which the control error is changing

The relay unit is shown in Figs. 52–53. In order to keep air consumption to a minimum, and so as not to restrain the measuring instrument to which the

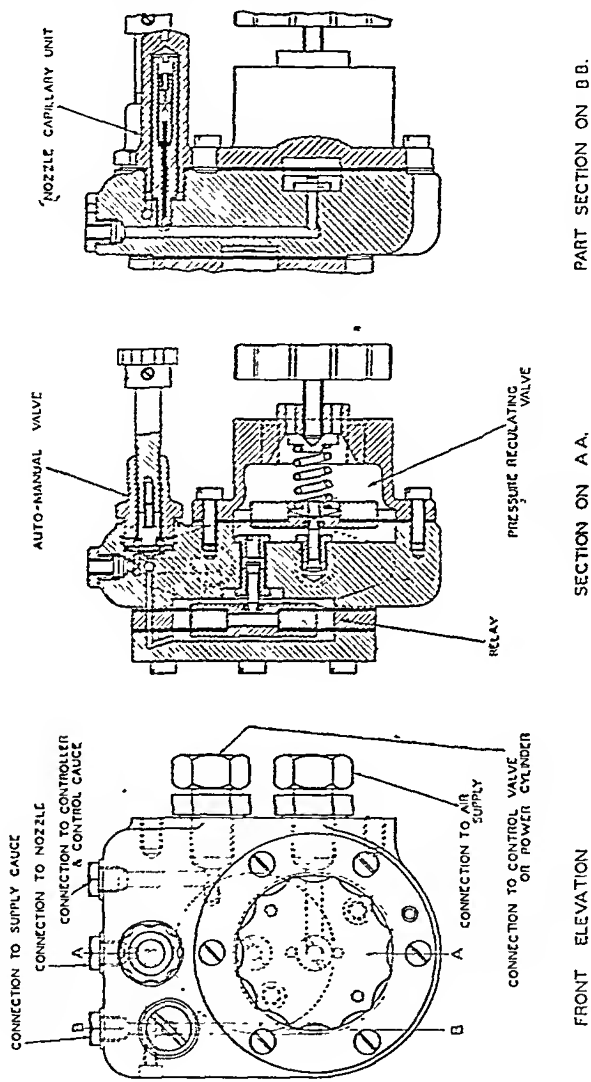

Fig. 53.—Kent relay unit

controller is connected, the control nozzle has a very small bore, and deals with extremely small quantities of air, which would take too long to change the position

in the control valve, or other means of regulation if a relay were not employed The relay is combined with the reducing valve, nozzle throttling resistance and auto/manual selector valve The relay consists of two diaphragms, mechanically connected at their centre The pressure from the nozzle is connected to the primary diaphragm chamber, so that there is a force proportional to this air pressure acting on the second diaphragm through the attachment between the two diaphragms The second diaphragm has a small hole in its centre which is normally covered by a needle valve, but which, when open, permits air to escape from the secondary diaphragm chamber to atmosphere through the space between the two diaphragms The needle valve carries a second cone which locates in a seat arranged in the air supply connection to the secondary diaphragm chamber, so that when air pressure increases in the primary diaphragm chamber, the resulting force will move the diaphragm centre assembly in a direction which will cause the exhaust end of the needle valve to close the exhaust hole, and raise the inlet end cone off the seat, permitting air to pass into the secondary chamber, and increase the pressure until the centre of the diaphragm assembly takes up its null position again with both inlet and exhaust valves closed

Under these conditions, equal or nearly equal pressures will exist in both diaphragm chambers The pressure existing in the secondary side of the relay is led to the central valve and the proportional side of the bellows chamber in the control mechanism, or in the case of the derivative controllers to the derivative resistance throttle valve

Reference to Fig 53 should make the operation of the relay clear It is shown separate from the pressure regulator for the sake of clarity

The *pressure regulator* is diagrammatically indicated in Fig 52 and is arranged to reduce the supply air to a standard pressure of 17 lb/in^2 when operating on automatic control or to any pressure between 2 and 12 lb/in^2 when operating on manual control

The *nozzle resistance* is in the form of a short length of capillary tube carried in a suitable mounting Its purpose is to restrict the flow of air to the control nozzle The mounting is made readily accessible so that it can be removed and if necessary, a new capillary fitted if it should at any time become choked

The *auto/manual selector valve* is an on off valve in the connection between the nozzle throttling resistance and the nozzle It renders the controller inoperative during manual control when the position of the control valve is regulated by the manipulation of the pressure regulator hand wheel

The main air inlet is connected to the relay unit at the lower union projecting from the right hand side of the body The connection to the control valve is made at the upper union projecting from the right hand side of the body

The *throttle range adjuster* is a pointer *G* which indicates on a scale mounted on the controller mechanism It is scaled in percentage of meter pen travel

necessary to cause the control air pressure to change through its full range of from 2 to 12 lb./in.^{2}. Reducing the scale reading increases the proportional sensitivity.

The *floating and derivative throttle resistance valves* are provided with micrometer adjusting means. Opening the floating needle valve *increases* the floating sensitivity, i.e. increases the rate of re-set. Opening the derivative valve *decreases* the amount of derivative effect. Both valve micrometers are scaled in needle travel.

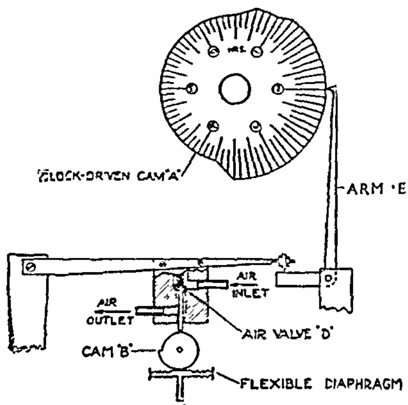

Fig. 54.—Principle of the Tycos time-temperature device
Showing "two-rise" and "two-hold" cam

Time-temperature control with air-operated controllers

It is sometimes desirable to have automatic means of heating or cooling according to a specified time-schedule. This can be readily done with air-operated controllers by suitable continuous adjustment of the pilot valve.

The time-temperature operating device fitted on the *Tycos* instruments consists of a large cam, *A* (Fig. 54), driven by clockwork at a definite speed. A definite contour which has been cut on this cam to suit the requirements of the operation is followed by an arm *E*, which in turn raises or lowers the whole of the valve seating. The valve itself is kept in contact with the capsule by means of a spring. Movement of the seating away from the valve consequently allows more air to pass to the diaphragm valve to open it, and thus allow more heating medium to pass.

A "blow-off" device is incorporated, which consists of an auxiliary air-valve mounted on the instrument directly below the operating cams. At the expiration of the predetermined period, this valve functions, terminating the process. A stop connected to the blow-off line automatically stops the clock and enables the operator to know the exact time at which the operation terminated.

If connected to the main air supply, the clock will stop should the air supply fail, and the time can be noted by the operator The clock can be started or stopped by hand

A " split cam " can be furnished, which can be used in a process requiring the admission of water for cooling at the end of the heating period , the cam allows the water valve to remain open until the end of the time period, when this valve will shut off automatically

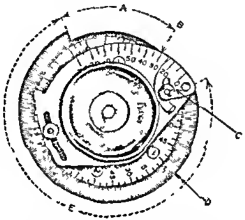

Fig 55—Tycos adjustable lift cams

(A) Section of cam covering initial temperature period (temperature is 100° F in this case)
(B) Indicates setting point of cam (30 minutes in this case) Temperature begins to rise at this point
(C) Adjustable rise sector regulating time of temperature rise (112° F in this case difference between 100° F and 212° F)
(D) Blow off arm or timing device regulating time of holding period (set for 1 hour in this case)
(E) Section of cam covering holding period (212° F in this case)

Adjustable "lift-cams" (Fig 55) are used for controlling the temperature and time of any operation requiring a variable rate of rise or fall between two temperatures A superimposed cam on the main cam can be swung in and out so as to overlap the main cam if necessary, and deflect the tracing lever as required

In the *Drayton* regulator of the air-operated type, the volatile liquid operates a Bourdon spiral tube The pilot valve is operated by a system of links from this tube Continuous temperature records are made on a flat paper covered disc The time-temperature device in this regulator takes the form of a celluloid

disc of the required contour, superimposed on the temperature-record disc. The contour is followed by a pointer connected to the pilot valve by links. Since the temperature-indicating pointer and the control pointer have parallel motions, it is a fairly simple matter to cut out a celluloid disc of the required contour.

Unsystematic response in air-operated controllers

Systematic behaviour of the control system in a pneumatic controller requires a constant supply of clean air. Oil or water in the supply air may cause sluggish response of an open-and-shut instrument, or erratic or changed response of a throttling instrument, even if operation does not cease entirely. Each instrument should be provided with its own individual air-filter unit. In addition, however, it will often be necessary to provide large separator tanks on the air-supply headers. In extreme cases, float-actuated drain-valves may be needed to avoid flooding of the system. Compressor after-coolers are always a help. A proportional instrument usually requires not only clean air but air at constant pressure, so that the instrument need not continually correct for erroneous valve-motions resulting from fluctuations of the air supply. However, this requirement is easily met by providing each controller with its own individual air-pressure reducing valve. This is a desirable feature, both to promote reliability through freedom from group failure of several instruments on a common valve, and to reduce installation costs by bringing high-pressure supply air in small-bore copper tubing instead of low-pressure air in large-bore pipe.

CHAPTER 9

Thermostats using boiling liquids

A CONVENIENT laboratory method of maintaining the temperature of an object constant at temperatures in the range from 0° C to about 400° C is to immerse it in the vapour of a boiling liquid, or to suspend it in a double walled vessel, between the walls of which the vapour circulates Yet another method is to suspend a tube, or number of tubes, from the cover of the vessel containing the boiling liquid, and place the objects to be maintained at a constant temperature in these tubes Steam or sulphur vapour[1, 2] are often employed for this purpose, giving temperatures of 100° and 444 6° C respectively under normal barometric pressure Other liquids and materials which are solid at room temperature but melt at convenient temperatures for the particular purpose may, of course, be used Most of the bath liquids mentioned in Chapter 3 may be used in this connection, and the restrictions mentioned there will apply here also

The method provides a simple means of maintaining a constant uniform temperature in a comparatively large volume

Care must be taken if closed ended tubes are suspended in the vapour to provide the uniform temperature space, that the distance between the lower ends of these tubes and the surface of the boiling liquid is sufficiently great to prevent splashing of the liquid on them , otherwise their temperature will be affected It is also beneficial to provide the tubes with radiation shields in order to prevent loss of heat by radiation from them to the cooler walls of the container These shields may take the form of metallic tubes concentric with, and larger than the main tubes, and drawn in at the top end to fit the main tubes

To avoid superheating the vapour when external heating is applied the heat should not be applied too close to the surface of the liquid , and also for a similar reason, a poor conductor should be used for the material of the container Such materials as silica, pyrex, or other hard glass are suitable Great care has to be taken to avoid fracture on reheating the solidified contents of such containers By the use of an electric heating coil completely immersed in the solid, this trouble can be avoided The leads can be sealed in the walls of the container, preferably below the level of the solid, to obviate the possibility of superheating the vapour The container can, with this method of heating, be adequately lagged Loss of vapour is minimized by using a condenser,

which, for most cases, need only consist of a long open-ended tube in the top of the vessel.

On the other hand, constancy of temperature for long periods of time cannot be maintained satisfactorily unless precautions are taken to obviate the effect of variations of atmospheric pressure, for the boiling-point of a liquid may change by several degrees due to this cause. For accurate work, such variations can be eliminated by sealing the bath in an air-tight manner, and compensating for changes from atmospheric pressure by the addition or removal of small quantities of air as required. This arrangement gives a high degree of constancy, and no appreciable deviations can be detected with a sensitive thermometer.

Using commercial petroleum, or a similar liquid containing a number of constituents of different boiling-points, it is possible to arrange that any

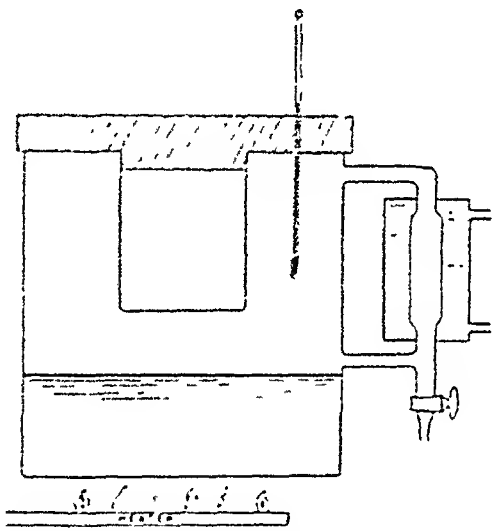

Fig. 56. Arrangement for boiling-liquid thermostat

temperature within a limited range can be maintained. With petroleum the range is about 40° C to 75° C.

In boiling a mixture of liquids, the concentration of the vapour is different from that of the liquid, and if the vapour is allowed to escape, the boiling-point will rise continuously to a certain limit. When the required boiling-point is reached, the system may be sealed to maintain the concentration at a constant value.

One form of apparatus for this purpose is illustrated in Fig. 56. It consists of a double-walled vessel, the space between the two walls containing the liquid and its vapour. The object to be kept at a constant temperature is contained

in the inner vessel, the upper end of which is well insulated to prevent the effects of external temperature-differences For greater simplicity, this double-walled vessel may be replaced by a vessel in which the object is directly suspended in the vapour, providing that the object is not attacked by the vapour and also that its frequent removal and replacement is not necessary In either case the liquid is boiled and the vapour passes into the condenser, whence the liquid formed flows away through the tap and is collected in a convenient vessel When the desired temperature is attained, as indicated by a thermometer immersed in the vapour, the tap is closed and the condensate thereafter returned to the vessel, thus keeping the concentration constant, and giving a liquid with a constant boiling point The condenser may be stopped if desired

The same result, but with greater difficulty in securing a selection of temperatures when using the same liquid, may be attained by increasing the pressure on the liquid and so raising the boiling-point

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CHAPTER 10

Thermostats using the expansion of solids

The expansion of solid materials with rise in temperature may, broadly speaking, be used in two ways to control temperatures. Use may be made of the property either in the simple form of direct expansion, where the material has relatively free movement to make and break the electrical control circuit, or it may be employed in a differential manner in the form of bimetallic strips. This latter arrangement will be described in a later chapter.

Thermostats depending on the expansion of solid materials are very reliable, providing the expansion material is suitably selected and treated. The fact that linear expansion is usually a straight-line function of temperature is also an advantage, since the accuracy of regulation is not diminished at high temperatures. As the amount of expansion of the material is small, the control mechanism has to be sufficiently delicate to respond to small movements. This may be arranged by the use of a system of levers to magnify the movements, or the expanding material may operate a pilot valve controlling a compressed-air or steam supply. In some instances a combination of both methods is utilized.

One simple form of thermostat of this type consists of a hollow metal block in which a hole is drilled to take a porcelain rod. The movement of the porcelain rod in or out of the block with change of temperature causes electrical contacts to be made or broken through the agency of levers. The metal block may be made of aluminium for temperatures up to 500° C; aluminium bronze for temperatures up to 700° C; and 18–8 chromium-nickel steel for temperatures up to 1000° C. The block may be cylindrical with a one-inch wall between the constant-temperature zone and the heating element. The diameter of the block should be roughly the diameter of the constant-temperature zone plus 2 inches; the length should be the length of the constant-temperature zone plus 12 inches. Bushings may be used inside the block to reduce the heating space.

The more usual form of instrument consists of a tube of metal of relatively high expansion, such as brass, in which is contained a rod with a negligible or very small coefficient of expansion. This rod transmits the movements of the tube to a switch or valve arrangement. This arrangement results in a rapid response of the sensitive element to fluctuations in temperature, which would not be the case if, alternatively, the sensitive element were contained in a non-expanding tube, as is sometimes found.

Simple form of solid-expansion thermostat

In Fig 57, A is a brass tube immersed in the liquid under temperature-control One end of a nickel steel rod B is held by a spring S against the end of the tube, while the other end E is free to press upon or recede from the conical valve seating F, thus controlling the passage of water or compressed air from the pipe H to D (connected to the diaphragm chamber of the main control-valve) With rise in temperature, the rod is withdrawn from the valve F by the expansion of the tube A, allowing more water or air to pass through to the diaphragm, thus increasing the pressure and causing the main valve to close

The *Chevenard*[1] *dilatometer* can be modified to act as a thermostat The expansion in the heating furnace or space of a bar of nickel-chromium alloy is magnified by a series of levers, which move a pair of prongs into one or both of two mercury cups One prong enters the mercury slightly before the other

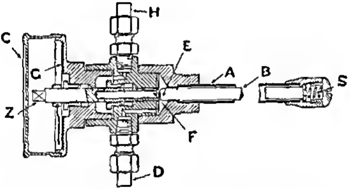

Fig 57—Thermostat depending on the expansion of solid material

and energizes a relay which puts a certain amount of resistance into the furnace circuit If the temperature continues to rise the second prong enters the mercury in the other cup, and through another relay more resistance is put into the furnace circuit

Chevenard has also designed an apparatus (Fig 58) in which the extension of a length of wire with increase in temperature (due to increase in the supply current which passes through it) causes a resistance to be put into the circuit A part of the supply current is passed through a length of nickel chromium steel wire contained in a vertical Pyrex glass tube The instrument is adjusted to be in equilibrium at the required temperature, and any fluctuation in the current supply causes a change in the temperature of the wire, and consequently in its length This change in length is transmitted to a long needle which, through a linkage, moves a lever with prongs dipping into mercury contacts Fluctuations in atmospheric temperature are compensated for by making

the link lever bimetallic, so that as it bends with change of temperature its point of contact with the needle is proportionately affected.

Expansion of the furnace tube

It is possible to use the furnace tube or core itself as the expanding medium, and this results in a rapid response to temperature changes. The method has been successfully applied to the regulation of furnaces used in laboratories. The tube can be of iron, nickel or chrome-nickel, according to the required

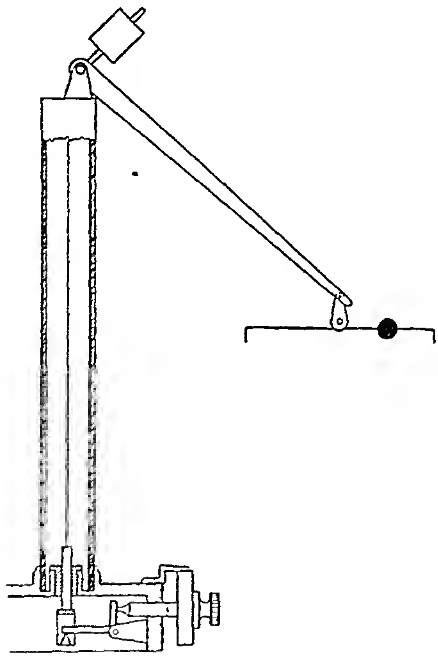

Fig. 58.—Chevenard regulator

temperatures, and is fixed securely at one end in a clamp, whilst the other end is free to expand and operate a switch through a system of levers. Fig. 59 illustrates diagrammatically the principle of such a form of regulator, in which one end *B* of the tube *A* is fixed in a support, the other end *C* bearing against a lever which operates a switch *D*. The supports for the lever are water-cooled to prevent expansion.

The "Arca" regulator.—The variation in length with temperature of a strip of ebonite is made use of in the "Arca" regulator. This strip of ebonite controls a special form of relay, which, together with the strip, is mounted in the chamber to be regulated. Gas or other valves may be operated by means

of a power cylinder The principle of the apparatus may be understood by reference to Fig 60, This figure illustrates diagrammatically the control of *steam pressure* but the general principle is the same Increase or decrease of temperature causes a long ebonite strip connected through a spring to the lever *l* to move this lever further from or nearer to the jet *m* and so control the rate of flow of water from the nozzle of the jet to the water pipe The strip is directly connected with the lever *l* instead of the bellows *k* Restriction of the flow of water causes a rise in pressure in the pipe *h* and in the space beneath the flexible diaphragm *n* in the pilot valve *b* causing the latter to rise and open suitable ports to permit the supply of water to flow into the power cylinder *c* as well as through the pipe *h* to the jet As pressure water is supplied to the upper part of the cylinder *c* the piston falls *and pulling down the chain increases* the opening of the gas supply valve If the temperature rises too high in the

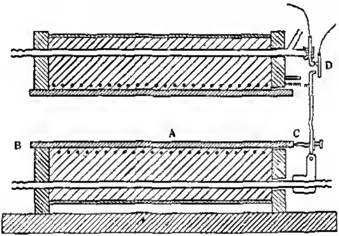

Fig 59—Use of the expansion of a furnace tube to control temperature

chamber the lever moves further away from the nozzle *m* with the result that the jet flows more freely and pressure falls in the valve chamber *b* The spring above the diaphragm forces the valve down so that through suitable ports the operating cylinder *c* is put into communication with the waste pipe and the piston moves the gas valve correspondingly In practice the relay *a* and pilot valve *b* are made in one unit

It will be realized that the working principle of this regulator is in effect similar to that operated by the expansion of a liquid through a pilot valve controlling air pressure as described in Chapter 8

A number of other physical properties may be controlled by a slight modification of the regulator To apply the regulator to electrical work the movement of the jet lever is controlled by a relay The position of the armature of this

relay is dependent on the voltage across, or the current in, the apparatus to which the regulator is connected. The regulator has been applied to control the position of the electrodes in an electric furnace. The electrodes are moved by hydraulic cylinders controlled by the regulator.

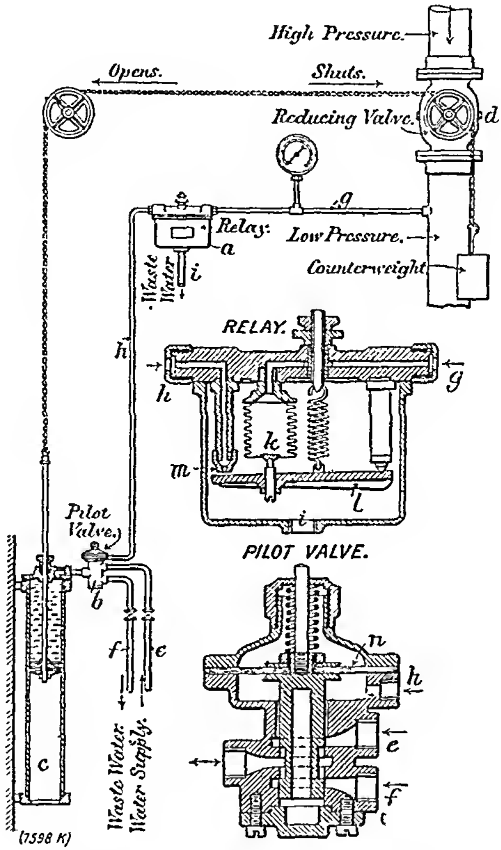

Fig. 60.—Principle of "Arca" regulator

Reference

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CHAPTER 11

Bimetallic-strip regulators

THE expansion of metals with temperature is made use of in a special way in thermostatic bimetals Two metals, or more generally two alloys, of widely different coefficients of thermal expansion are firmly bonded together over their surface of contact by brazing or welding Change of shape will occur when the temperature changes, and this change of shape, magnified if necessary, can be utilized for temperature control purposes Thermostats of this form, depending on the materials used, can be used up to a temperature of about 550° C They are simple, fairly robust and reliable if adequate care is taken in their manufacture and use For these reasons such thermostats are very popular for many industrial and domestic heating appliances

Choice of components for bimetallic strip

The difference in the coefficients of expansion of the two components is one of the prime considerations in the selection of these components The expansion of alloys, particularly those with low coefficients does not always increase regularly with temperature abrupt changes in the direction of the expansion temperature curve often being found, with a large increase in the expansion at higher temperatures so that the element having the lower co efficient must be suitably selected with regard to the required working temperatures

Materials for the high expansion component, in addition to having a high coefficient of expansion should be easily brazed or welded, should develop high elastic properties as a result of cold-working and should have good heat-resisting properties

A stable zero position is largely dependent upon the strength and elasticity of the components At the junction of the two components on heating there will be tensile forces in the higher expanding material and compressive forces in the lower If e strengths are widely different, there is a possibility of exceeding the elastic limit of the softer material during heating and cooling so that the bimetal strip does not regain its original shape on cooling It is therefore advisable to combine components of similar strengths and, if possible, of equal and great elasticity

A further point in this connection is that in addition to internal stresses, the bimetal may be subject to stresses due to restraints, loads, etc , which may

affect its performance if these stresses exceed the elastic limits of the materials at high temperatures.

Since the accuracy of a bimetallic strip depends principally on the elastic properties of the combination, it is therefore essential to use the materials in a state hardened by cold-rolling and carefully heat-treated to obtain the highest possible strength and elasticity. Subsequent treatment which will affect these properties adversely should be avoided. Strains resulting from manufacture, which remain in the combination, should be removed by heating to about 50° C above the intended working temperature and slowly cooling.

If cold-treatment such as bending, rolling, etc. is to be done, this should be carried out at a temperature lower than that which the part is expected to reach in service.

If a heat-treated part requires further mechanical adjustment, it should be given a further heat-treatment after such adjustment is carried out. Parts being heat treated should be free to deflect or be restrained in the same manner in which they will be in service.

After mounting and before final adjustment of accurate bimetallic thermostats they should be given several cycles over the entire temperature range, heating and cooling from below the minimum to above the maximum temperature under conditions similar to those to which they will be exposed in service.

For the element of low coefficient of expansion, Invar (36 per cent nickel, 0·1 per cent carbon, 0·5 per cent or less of manganese and the remainder mainly iron), is commonly employed. This material may be used up to temperatures of about 120° C. A nickel content of 40 per cent is used up to 230° C, 42 per cent to 340° C and 46 per cent for temperatures up to about 440° C. For temperatures higher than these values the thermal expansion is comparatively large, and the difference in expansion between the two components of the bimetallic strip diminishes, thus rendering the curvature so slight as to be of no practical use. One point of importance may be mentioned here. Invar, upon heating, expands initially with a coefficient of 1×10^{-6}, about equivalent to that of iron or nickel, and then after the lapse of a few minutes at the same temperature, contracts to show a normal coefficient of expansion of about $0{\cdot}4 \times 10^{-6}$. Consequently, in using Invar under conditions where rapid rates of heating or cooling are involved, this temperature-time hysteresis effect may influence the deflection of bimetals by an appreciable amount. As for the properties of Invar, it is very strong and ductile. It is generally ferromagnetic but becomes paramagnetic in the region of 165° C. Above 200° C its expansion is nearly that of steel.

With the small-expansion element Invar, the large-expansion elements sometimes used are Constantan (nickel 45 per cent, copper 55 per cent) or Monel metal (nickel 65 per cent, copper 30 per cent, iron 5 per cent, manganese

4 per cent), and for certain purposes iron-nickel-molybdenum alloy (nickel 22-27 per cent, molybdenum 6 per cent, remainder iron). The deflection constant when using Monel metal, however, is rather low. These combinations are suitable for temperatures up to about 180° C. For higher temperature-ranges up to 400° C a nickel steel (42 per cent nickel) as the low-expansion component with nickel constantan as the high are employed; while for even higher temperatures, such as 500° C, a nickel steel (42 per cent nickel) is used with an alloy of iron 68 per cent, nickel 27 per cent, and molybdenum 5 per cent. Recent developments have resulted in the use of nickel chromium alloys containing from 18 to 20 per cent nickel and from 3 to 11 per cent chromium and many other combinations are now commercially available from, for instance, Messrs. Henry Wiggin & Co. Ltd., Birmingham.

The expansion of some alloys changes fairly rapidly over a certain temperature range. In some instances being low up to a certain temperature, then increasing rapidly and thereafter falling off again. This peculiarity can be applied usefully for control at a fixed working temperature which is within the maximum expansion range of the chosen alloy. This minimizes excessive stress taking place at the adjoining surface of the two components.

A combination of 42 per cent nickel and 58 per cent iron with 12 per cent nickel, 83 per cent iron, and 5 per cent molybdenum has slight curvature up to about 150° C, then increases rapidly between 150° and 400° C, whilst above 400° C further increase in curvature is very slight. The useful working range therefore lies between 150° C and 300° C. The useful working range of 42 per cent nickel and 58 per cent iron with Invar lies between 250° C and 350° C. Below 250° C the strip curves in the opposite direction to that above 250° C.

In selecting a combination of metals preference should be given to that which gives the greatest change in curvature near the operating temperature rather than to one which has the greatest total curvature up to that temperature.

A fact which must be borne in mind when choosing materials for components of a bimetal which is to be heated by conduction is that Invar and most of the high temperature bimetal components, such as chromium nickel steels, are poor conductors of heat.

Dimensions of bimetal

The dimensions of a bimetallic strip will have a bearing on the extent of curvature and force exerted by the free end. The amount of bending will increase as the strip becomes thinner, but the force which the free end of the strip is able to exert is proportional to the third power of the thickness of the strip. The force, consequently, decreases more rapidly than the curvature increases with thinness. It must, however, be sufficient to operate a mechanism or to open or close a contact with certainty. A number of thin bimetallic strips clamped at one end are sometimes used to provide sufficient force.

Increased length and decreased thickness of a strip renders it sensitive to shock and other mechanical effects, and causes its action to be uncertain. A small movement of the free end is usually sufficient, particularly if the current passing is sufficiently small to avoid arcing at the contacts. The deflection of the free end of a bimetallic strip is proportional to the square of the length, when the deflection of the free end is relatively small in comparison with the length of the strip. For a definite thickness, the force exerted by the free end is inversely proportional to the cube of the length of the strip ; with a strip of constant length it is directly proportional to the cube of the thickness. Thus the force at the free end of a bimetallic strip remains constant if the length is increased in the same proportion as the thickness, but the resulting deflection becomes proportionately greater. The amount of deflection can therefore be increased, and the force available for making and breaking contact kept the same, by increasing the length or decreasing the thickness, if at the same time the thickness is proportionately increased or the width increased proportionately to the third power respectively. Increasing the width does not decrease the amount of deflection. The radius of the bend should be at least five to eight times the thickness of the strip.

It is possible to arrive at the characteristics of a bimetal mathematically,[1-5] but the derived formulæ are rather complicated and the calculations do not always give accurate results. Nevertheless, the approximate figures obtained serve as a guide. In the formulæ obtained by Timoshenko[1] it is assumed that the coefficients of expansion of the two elements remain constant during heating, that the friction at the supports is so small that it can be neglected, and that the width of the strip is very small. The curvature of such a strip is given by the equation—

$$\frac{1}{s} = \frac{6\,(\alpha_2 - \alpha_1)\,(t - t_0)\,(1 + m)^2}{h\,[3\,(1 - m)^2 + (1 + mn)\,(m^2 + 1/mn)]},$$

where s = radius of curvature of strip,

α_1 and α_2 = coefficients of expansion of the two metals,

h = thickness of bimetal strip,

$m = \dfrac{a_1}{a_2}$ = ratio of thicknesses of the component strips, and

$n = \dfrac{E_1}{E_2}$ = ,, ,, moduli of elasticity,

t_0 and t being initial and final temperatures of the strip.

If the thicknesses of both metals are equal,

$$a_1 = a_2 \text{ and therefore } m = 1.$$

Then $$\frac{1}{s} = \frac{24(\alpha_2 - \alpha_1)(t - t_0)}{h(14 + n + 1/n)}.$$

Again, if $\frac{E_1}{E_2}$, that is $n_s = 1$,

then $$\frac{1}{s} = \frac{3}{2}\frac{(\alpha_2 - \alpha_1)(t - t_0)}{h}$$

The equation for the deflection of the strip is given by

$$\delta = \frac{l^2}{8s},$$

where l is the length of the strip and s the value obtained from one of the foregoing equations

For use with these equations it may be stated that the brass invar type of bimetal has a modulus of elasticity of approximately 17,500,000 lb per square inch, and most of the medium and high temperature bimetals have moduli of elasticity of about 25,000,000 lb per square inch at room temperature These values are lowered by 10 to 20 per cent at elevated temperatures

Instead of the customary gradual bending with increase of temperature, a sudden buckling of the composite strip at the required temperature is sometimes utilized For this purpose the two ends are fixed or in the case of a composite disc, the circumference is held rigidly in a frame The equation given by Timoshenko for such a strip, assuming the same conditions as before, and that the strip is so bent that the more expansible element is on the concave side, is—

$$t - t_0 = \frac{1 + 6\,\delta_0^2\left(\frac{1}{3} - \frac{1}{9}\frac{h^2}{\delta_0^2}\right)^{\frac{1}{2}}}{\frac{3}{14}\frac{l^2}{h\,\delta_0}(\alpha_2 - \alpha_1)},$$

where δ_0 = initial deflection of strip,

h = thickness of strip,

l = length of strip,

t_0 = initial temperature of strip, and

t = temperature at which sudden buckling occurs

The temperature (t_1) of backward buckling on cooling is given by

$$t_1 - t_0 = \frac{1 - s}{1 + s}(t - t_0),$$

where $$s = 2\,a\left(\tfrac{1}{3} - \tfrac{1}{3}a\right)^{\frac{1}{2}}$$

Weber[2] suggests a somewhat different equation for the bending of straight strips. With one end of the strip clamped, the deflection dS of the free end is stated to be related to the temperature by the equation—

$$\frac{dS}{dt} = \frac{4\,L^2\,R\,a^1}{5\,\delta\,\theta},$$

where L = effective length of bimetal;

a^1 = difference between the two linear-expansion coefficients;

$\delta = \frac{d_1 + d_2}{2}$ = the average of the two thicknesses;

$$R = \left(1 + \frac{\sin^2\varphi}{\varphi^2} - \frac{2\sin\varphi\cos\varphi}{\varphi}\right)^{\frac{1}{2}};$$

θ = central angle of arc; and

$$\varphi = \frac{\theta}{2}.$$

$\frac{dS}{dt}$ is greatest for a straight strip ($\theta = 0$).

When the bimetal is made in a spiral form, $\frac{dS}{dt}$ is greater than for a simple bimetal ring of the same heat-capacity; but the force F for a spiral is much decreased compared with that of a single ring having the same mass or the same value of $\frac{dS}{dt}$.

$$F \sim \frac{M\,I}{L^3} \sim \frac{M\,\delta^3\,B}{L^3},$$

where $\left.\begin{array}{l} L = \text{effective length} \\ B = \text{width} \end{array}\right\}$ of bimetal;

δ = arithmetic mean of both thicknesses;

M = elastic modulus; and

I = moment of inertia of the cross section.

Incidentally a new bimetal may show considerable decrease in $\frac{dS}{dt}$ over a period of time. This may be minimized by thermal massage before calibration.

A test-method schedule has been prescribed[6] by the American Society for Testing Materials for testing thermostat metals.

The usual shapes of bimetals

Some of the shapes commonly used for bimetals are illustrated in Fig 61, which also provides information concerning their characteristics

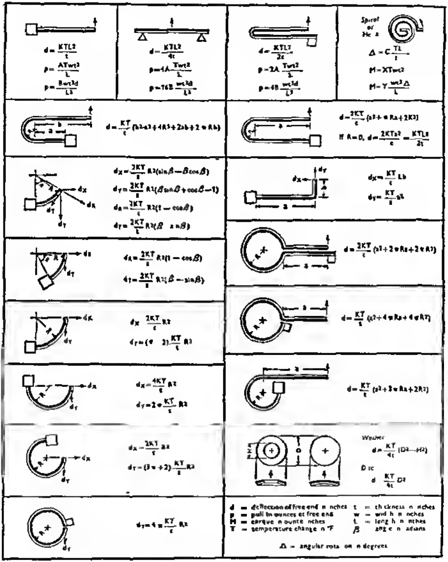

Fig 61 —Shapes of bimetals

K A B C Y Z are constants of the individual materials values of which can be obtained from the makers of the materials e g Henry Wiggin & Co Ltd Wiggin Street Birmingham

Bimetallic-strip arrangements

The usual method is to place a strip or disc of the composite materials in the heated space, one contact being on the strip and the other on a convenient contact pillar nearby. When adjustment of the setting has to be made, say in an oven, trouble is sometimes experienced due to the binding of the thread of the adjusting screw, if it has been exposed to a moderately high temperature. Further, the contacts may be fouled by oils, varnishes, or other substances vaporized by the heat of the oven. It is advisable, therefore, where possible, to arrange that the adjustment and the contacts shall be outside the oven. This can be done by using a spiral bimetallic strip which moves a spindle emerging from the oven. The spindle then works the contacts. Alternatively, with a disc type of bimetal, the movement can be transmitted by a rod bearing on its surface.

It is sometimes found with bimetallic-strip thermostats that the contacts maintain themselves a small distance apart for considerable periods, while sparks pass between them and a singing sound is emitted. This effect is due to electrostatic attraction between the contacts, which periodically close and open again. By fitting a compensating plate[7] above the upper contact and connecting this to the lower contact, the critical "singing" conditions may be eliminated and normal operation of the contacts secured.

If any appreciable current is controlled through the contacts, a certain amount of wear is bound to ensue. The cause of this wear arises from a number of complicated factors, and the reader is referred to a paper by Betteridge and Laird[8] on this subject.

Other uses of bimetallic-strip thermostats

Cold-junction temperature control.—In a thermo-electrical circuit the electromotive force generated by the thermocouple depends, among other things, on the difference in temperature between the hot junction in the furnace and the cold junction at the head of the thermocouple. If the temperature of the cold junction varies, the readings of the galvanometer—either indicator or recorder—will vary, although the hot junction may be at a constant temperature.

Various methods have been devised to control the temperature of the cold junction, and the decision as to which method should be adopted depends on the degree of accuracy required and on the conditions under which the apparatus is to be installed. A convenient way of controlling the cold-junction temperature is to place the junction in an electrically controlled thermostat.

The Cambridge bimetallic type thermostat for this purpose (Fig. 62) consists of four heater coils in series with two high-resistance carbon filament lamps giving a red and green light respectively and placed outside the apparatus.

A bimetallic strip *S*, carrying an adjustable platinum contact at its end, is so arranged that when a definite temperature is reached, the distortion of the strip causes contact to be broken, which puts both lamps into the circuit. The resistance of the lamps decreases the number of watts dissipated in the heater coils *H*, and the temperature then drops until the bimetallic strip makes contact and shunts one lamp, thereby again increasing the number of watts dissipated by the heater coils The bimetallic strip, heater coils and cold junction are immersed in an air bath, placed in an outer metal tank, the space between the two vessels being well lagged to prevent undue heat loss The lamps act as pilot lights, in addition to functioning as series resistances A number of

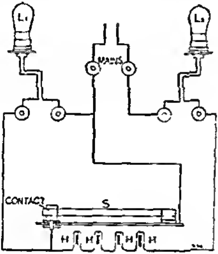

Fig 62 —Circuit diagram of Cambridge Bimetallic Thermostat for cold-junction control

thermocouples can be controlled by this thermostat. The cold junction temperature can be controlled to within about 0 5° C

A bimetallic regulator unit is available which consists of a bimetallic strip operating contact-points of tungsten, the whole being mounted in a small glass tube say 7 cm long by 1 cm diameter and filled with inert gas The unit has a low thermal capacity and the contacts do not become contaminated

Bimetallic strips do not always operate through the medium of contacts, but may be used to regulate a pilot valve which controls a supply of steam or compressed air to operate a main valve

Car thermostats.—As stated in another chapter the bimetallic principle is adopted[a] in the design of thermostats for regulating the temperature of the water-jackets of motor-cars An example of this type of thermostat is illustrated diagrammatically in Fig 63 This thermostat functions in a similar

manner to that described on page 69, but employs a bimetallic strip in place of a bellows. The bimetal is bent into semi-circular form, the ends being attached by means of two short arms to a lever. The longer arm of this lever terminates in a fork which raises the plate valve from its seating against the pressure of a spring. The heated water causes the strip to straighten and so move the lever by means of the two small connecting pieces.

Carburettors.—Thermostats have also been applied to adjust the carburettors of motor cars. The orifice of the jet can sometimes be varied by means of a needle-valve which permits of a greater flow of petrol when starting, which can be decreased by hand when the engine has warmed up. Other methods

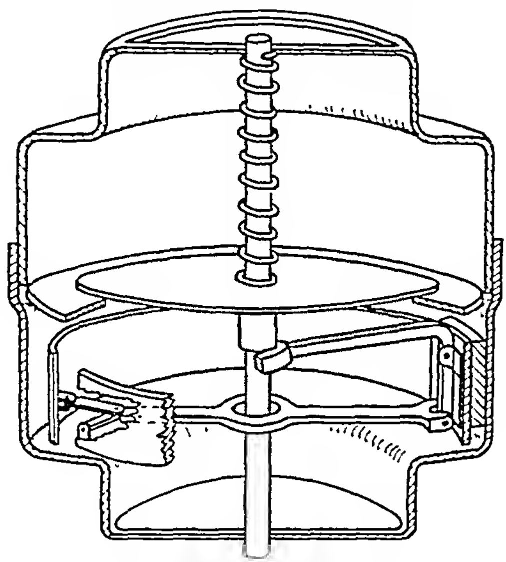

Fig. 63.—Car thermostat bimetallic-strip type

are to cut down the amount of air supply or to incorporate an auxiliary carburettor at this warming-up period. In all cases the actions can be made automatic with the assistance of a bimetallic element, situated either in the water system or attached to the exhaust manifold and connected electrically to the different control motions.

Fire alarms.—Thermostats are sometimes employed either to give warning by ringing a bell or to operate sprinkler devices to extinguish fires. They come into operation when the temperature of a room reaches a certain value. These devices may consist of bimetallic strips which close electrical circuits when they bend. A bell can be made to ring continuously until the temperature falls or the alarm is cut off.

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CHAPTER 12

Electrical-resistance thermostats

THE property of change of electrical resistance of a material with temperature has afforded the basis for the design of a number of regulators. In a very simple and inexpensive form, this property can be adapted to control temperatures within moderate and satisfactory limits of fluctuation, whilst by elaboration it can be arranged to control within very fine limits. Some of the less elaborate types will be described first.

Salt resistance

When using a large number of solder pots, it is a great advantage to have the heating automatically controlled so that the workman may devote his whole attention to the work in hand. The thermo-electric pyrometric control method, described later, is applicable to this work but is very expensive, especially when a large number of pots are in use, each requiring a separate control. The cost of the salt-thermostat method is comparatively low. The temperature is held constant within fairly close limits and the device is strong mechanically, the latter being a distinct advantage in the case of solder pots. The principle on which this class of resistance thermostat depends is that salts, oxides, and non-metallic materials in general have a negative temperature-coefficient of electrical resistance, that is, the resistance usually decreases rapidly as the temperature approaches the melting-point. Above the melting-point further decrease is slight. In a number of cases, salts decrease their resistance from about 1,000 to 5,000 ohms per centimetre cube down to 1 to 5 ohms per centimetre cube when the temperature passes through a range of 10° to 15° C (18-27° F) at or near the melting-point of the salt. The reverse change occurs on cooling the salt. This change in resistance is constant over long periods of time under conditions of alternate heating and cooling, such as obtain in solder baths. Hence the change in resistance of salts, when used in a cell contained in the solder pot and connected in series with a relay, may be used to operate a suitable switch for controlling the heating current of the pot. The salt resistance cell may be simply a steel tube.

The operation of the apparatus is very simple. For solder pots, a salt having a melting-point of about 400° C (752° F) is used. When the pot is cold, the resistance is high, but as the temperature of the solder rises, the resistance of the immersed salt decreases, but will not be low enough to allow sufficient current to pass to operate the relay until a temperature of approximately 400° C is attained, when the strength of the current is such as to trip the relay, which

in turn operates the switch cutting off the heating current The current will continue to flow through the salt resistance until the temperature of the solder has dropped and the resistance of the salt has increased so much that very little current passes The relay then returns to its original position and again switches on the heating current This cycle of alternate heating and cooling repeats itself as long as the pot is in use With gas- or oil-fired equipment, a magnetically operated valve for regulating the fuel supply is substituted for the switch

This salt-resistance thermostat has been used on solder and Babbitt metal pots, aluminium melting-pots and oil-tempering baths It has been found that the temperature remains constant to within 3° to 5° C at 500° C when the pot is not being worked

Metal resistance

Molten metal can be used in place of a salt, the specific resistance of a metal increases on melting to about twice that in the solid state A constant direct current, as control current, is passed through a mass of metal such as zinc, which is contained in the furnace or bath to be controlled Where close control is needed, potential-leads are taken from the inside of the metal to a reflecting galvanometer, the reflected light from which can fall upon a photo-electric cell The photoelectric cell then operates some form of relay, such as a thermionic valve, to control the furnace heating circuit A coil of copper wire may be used instead of molten metal A fuller description of the equipment used with these metal resistances is given below in the section dealing with Resistance Furnaces

Iron resistance —It is well known that the resistance of iron wire increases rapidly over a limited range of temperature This fact may be made use of to smooth out the effects of voltage variations in the heating-supply current to a furnace The iron wire is enclosed in an atmosphere of hydrogen to prevent oxidation, and is placed in the electrical circuit in such a way that sufficient current passes through it to cause it to glow. A slight increase in the applied voltage increases the temperature of the iron, causing a rise in its resistance and a subsequent diminution in the current allowed to flow through the wire It will be understood that the arrangement operates satisfactorily at a critical current only and is very little used for temperature-control

RESISTANCE FURNACES

The heating coil of electrically-heated laboratory furnaces can be used as the sensitive element of a thermostat The advantage of this arrangement is that no furnace space is occupied by any components of the thermostat Further, since the heater and sensitive element are identical, there is no thermal lag between the two

It is, of course, essential that the resistance of the heating coil should change to a reasonable extent with change of temperature, and the coil should not "deteriorate" rapidly; that is, the temperature-resistance relationship should remain sensibly constant with time. To meet these demands the materials which may be used are platinum, platinum-rhodium, molybdenum, nickel, chromel or other similar materials; but platinum or platinum-rhodium is preferably used at elevated temperatures. The disadvantages of a platinum-wound furnace are first, the expense, and secondly, it is not easy to arrange the winding to give a large zone of constant temperature, for owing to the high temperature-coefficient of resistance of platinum, hot spots tend to become hotter and vice-versa. Whatever kind of wire is used for the winding, it is desirable that the length of the winding be made five or more times its diameter in order to obtain a flat maximum in temperature-distribution along the axis of the tube.

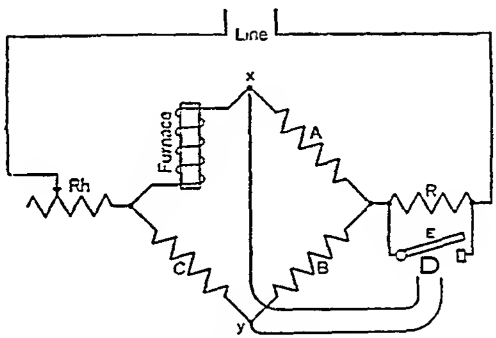

Fig. 64.—Schematic diagram showing basic principle of the Geophysical Laboratory thermostat

This use of the heating coil of the furnace as a resistance element and means of control forms the basis of the thermostat designed by White and Adams and collaborators [1–4] at the Geophysical Laboratory. The same principle has been used by a number of other workers, [5–11] to whom reference is made later in the chapter. The original design of White and Adams having been modified in several details, these latter will be described after an account of the original arrangement has been given.

Geophysical laboratory thermostat

The principle of the apparatus is that the heater of the furnace, having an appreciable temperature-coefficient of resistance, is associated with three other adjustable resistances whose temperature coefficients are negligibly small, to form a Wheatstone bridge. In the usual way, a change of temperature of the furnace resistance in either direction unbalances the bridge and produces

an unbalanced current in the circuit, its direction depending on whether the temperature has become higher or lower than that for which the bridge was balanced

The current from the mains passes through a fixed resistance *R* (Fig 64), and through a rheostat *Rh*, the latter being so adjusted that, with *R* in the circuit, too little current flows, and with *R* shunted by the switch *E* too much current flows, to maintain the furnace at the desired temperature A suitable device at *D*, described later, which includes a galvanometer actuated by the current in the galvanometer circuit of the bridge, opens and closes the switch *E* as the resistance of the furnace becomes too high or too low respectively When *E* opens, the current through the furnace is reduced, and the temperature and resistance of the heating coil decrease Similarly when *E* closes, the temperature and resistance of the heating coil increase Thus the resistance of the heating coil is caused to oscillate through a short interval on either side of some definite value, the average resistance remaining constant. The corresponding variation in the temperature of the wire of which the heating coil is made often amounts to several degrees, but the period of oscillation is seldom more than a few seconds, and because of lag, its effect on the constancy of temperature inside the furnace is usually too small to measure by ordinary methods

It may be mentioned here that Turner (see p 209) considers it inadvisable to improve the contact between the heating element and the sensitive element or regulator to such an extent as to identify them as is done in this form of regulator He argues that the heating coil on the furnace is hotter than its surroundings, including the furnace interior This would not matter if the temperature difference were constant, but the difference is proportional to the square of the supply voltage When the heater and regulator are identical a decrease in ambient temperature produces an increase in current supply and therefore an increase in the excess of heater temperature over the furnace space temperature Thus fall of ambient temperature and rise of supply voltage severally depress the furnace-space temperature

Reverting to the Geophysical Laboratory furnace, Fig 65 shows the complete diagram of the original apparatus, *F* being the furnace The bridge may be balanced by means of the sliding contacts *x* and *y*, by bringing them to the same potential, when the resistance of the furnace has any value between chosen limits Contacts *x* and *y* are connected to the galvanometer through a synchronous rectifier *S*, which may be short-circuited by the switch *Sw* when direct current is used The insulated boom (*b*) of the galvanometer is arranged to make either of the two contacts *a* and *c*, depending on the direction of the current through the galvanometer coil If these contacts were used directly to break the heating current, trouble would be experienced due to their sticking and sparking, and a satisfactory remedy is to use a triode valve as an intermediate relay As previously mentioned, the advantage of such a relay lies in the fact

that its operating current, which must pass through the galvanometer contact, may be made less than 1 micro-ampere. The boom of the galvanometer is connected to the grid of the triode T, whose plate current passes through a high-resistance relay R_1. The potentials of the contacts a and c are so chosen that when the galvanometer closes contact c, very little current flows in the plate-filament circuit of the triode and relay R_1 is open ; whilst when the galvanometer closes contact a, a moderate anode current flows and the relay

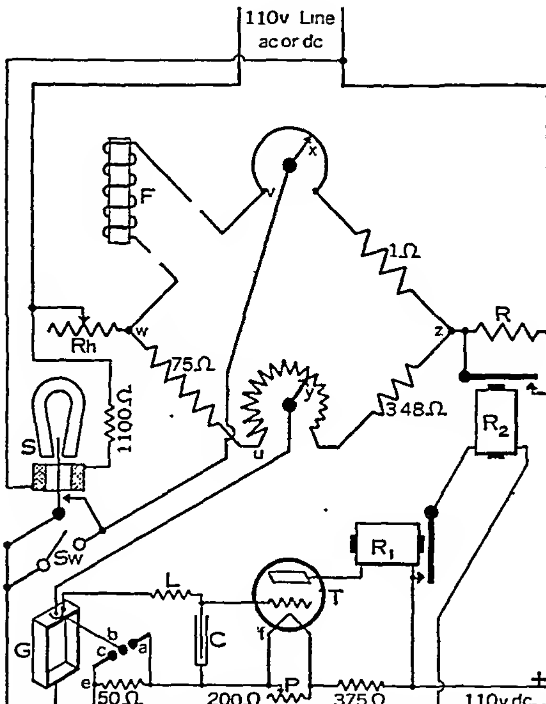

Fig. 65.—Circuit diagram of original Geophysical Laboratory thermostat

closes. The closing of R_1 causes R_2 also to close and to short-circuit the resistance R in series with the bridge and furnace.

The operation of the apparatus is as follows: Assume that the furnace is hot and the bridge balanced ; that the rheostat is adjusted so that with R in the circuit too little current flows, and with R short-circuited too much current flows, to maintain the furnace at its proper temperature ; and that the relay and galvanometer contacts are in the positions shown in Fig. 65. Since the relay R_1 is open, the extra resistance R is in circuit and the furnace is cooling ;

change, while for a cycle in which the on and off are unequal, the resultant change of resistance forces the intervals towards equality, and if the demand remains steady, soon brings them to equality The resistance changes have to be made slowly to avoid introducing instability or " hunting "

Auxiliary furnace—The electrical power supplied to the furnace varies as the square of the voltage or as the square of the current The thermostat may therefore be arranged as an auxiliary furnace to maintain a constant root-mean-square voltage or current for a main furnace This is an advantage in cases where the heater of the main furnace has, due to cost, to be made of cheaper material of low temperature coefficient or of material which may change its properties at high temperatures After equilibrium has been reached between the temperature of the auxiliary furnace and that of its surroundings, the mean power supplied to the auxiliary during each cycle depends only on the temperature of the furnace and that of its surroundings The influence of the surrounding temperature may be made negligible by operating the auxiliary furnace at a high temperature, say 1,200° C, while the mean resistance of the heater may be kept constant by making the heater of a material such as platinum, which does not deteriorate at this temperature Another method of compensating for variations in ambient temperature is by placing a copper coil in one arm (*A* in Fig 64) of the bridge The coil is wound on a metal spool and placed in the open near the bridge coils It is inadvisable to increase the thermal lag of the coil by covering it with say, tape to make it respond to temperature-changes at about the same rate as the furnace A slow drift of temperature will occur if the auxiliary furnace winding is kept at temperatures above 1,000° C for prolonged periods The drift is less with platinum-rhodium than with platinum winding For constant voltage the load is connected in parallel with the bridge, that is, across *w* and *z* in Fig 65, and for constant current in series with the bridge This method is useful to eliminate the effect of variable line-voltage where the usual arrangement of the thermostat is ineffective

Other forms of resistance thermostats

Dealing now with some modifications of the main details of the furnace, that suggested by Brown[15] may be considered first In order to prolong the life of the platinum element in the furnace, a large part of the heat may be generated by a more suitable resistance element An alundum tube is wound in three sections, the two outer sections being wound with Brightray ribbon in two layers (*A*, *B* and *C*, *D*—see Fig 67), separated by a layer of alundum cement The middle section is wound with Brightray ribbon and 35 S W G platinum wire, arranged as a double threaded screw in the same plane (*E*, *Pt*) The resistances are so connected that a Wheatstone bridge arrangement is formed with one arm consisting of the platinum resistance and the other three

of the Brightray windings, the latter having, of course, a lower temperature-coefficient of resistance. The bridge is in balance at one temperature only, and this temperature can be fixed by the variable resistance R_1, and the slide wire connecting A and Pt. When the galvanometer G is deflected, due to temperature-variation in the platinum winding, a contact, carried by its moving coil, touches one or other of two fixed contacts. The relay R is thereby energized and opens, or closes, a mercury switch connected across part of the resistance R_2. The current in the windings is therefore too large, or too small, to maintain the desired temperature depending on whether R_2 is out of, or in, the circuit. To minimize the effect of these fluctuations of temperature in the furnace space, the walls are made of an inner tube of silica, separated from the outer tube of alundum by a nickel sheath, which incidentally is earthed. The object of the nickel sheath is to prevent electrical leakage from the windings of the

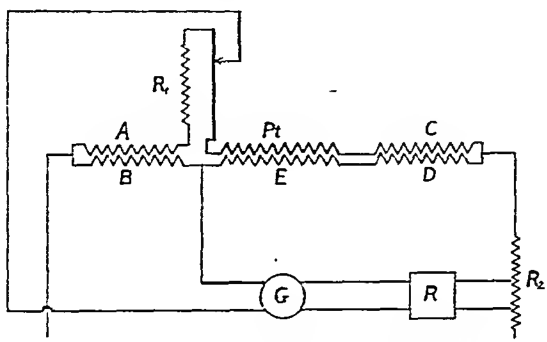

Fig. 67.—Brown resistance furnace thermostat

furnace tube. This thermostat can be arranged to give slow-heating or cooling by changing the balance of the bridge continuously. This is done by interposing a second slide wire between B and E. Connection is made to the galvanometer by a slider on this wire, moved at a suitable speed by mechanical means.

Separate coil and heater.—It is sometimes necessary to separate completely the thermometer coil and the heater, where the heating element has too low a temperature-coefficient, or where the furnace is heated by oil or gas. In other cases the separation is made for convenience. Under these conditions the coil can be made to function as a resistance thermometer only, and the current is then varied through the bridge by means of the relay. A separate thermometer and heater coil have been used by Prosser.[16] A further point of interest in this type of thermostat is that alternating current is used, which makes it possible to obtain a large amplification, by the use of valves, of any out-of-balance voltage in the bridge-circuit system of control.

Principle of the Prosser thermostat.—The thermostat circuit (Fig. 68) contains a relatively low-resistance, non-inductive platinum thermometer *a*, in a non-inductive bridge circuit, fed from a 4-volt winding on a transformer connected to the 50-cycle mains. Any out-of-balance voltage, due to the temperature of the thermometer deviating from the value set by the slide wire in the bridge circuit, is amplified by the two-stage valve amplifier *b* and then applied to the grid of the control valve *c*. The anode circuit of this valve is connected, through reversing contacts *d*, across a 110-volt winding on the mains transformer, but is in series with a large condenser *e*. This condenser is, in turn, connected to the grid circuit of a relay valve *f* which has a telephone-type relay *g* in its anode circuit. This relay controls the current to the furnace through another larger relay *h*, and also operates the reversing contacts *d*.

The sequence of operations can be understood more easily if it is assumed

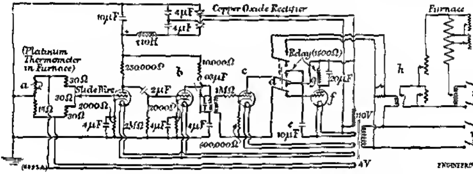

Fig. 68.—Circuit diagram of Prosser thermostat

that the temperature is correct, so that there is no out-of-balance voltage from the bridge circuit. Starting from a point in the cycle where the contacts are in the position shown in Fig. 68, i.e. when the grid of valve *f* is negatively charged and the rectified anode current is small, the control valve *c* will pass a small rectified current which slowly reduces the negative charge of the condenser *e*, thus gradually increasing the anode current in the relay valve *f*. At a certain value of this current the relay *g* will operate and reverse the contacts *d*. The rectified current passed by valve *c* will now charge the condenser in the reverse direction, and so gradually reduce the anode current in the relay valve *f*. The relay *g*, will, however, remain closed until this current has fallen to a certain value, when it will open and again reverse the contacts *d*, thus repeating the cycle. The values of the components are so chosen that the complete cycle occupies about 40 seconds, the furnace thus being supplied with maximum current for about 20 seconds, and with a reduced current for the subsequent 20 seconds.

Considering now the case when the temperature of the platinum winding is slightly low. There will then be an out-of-balance alternating-current voltage applied to the grid of the control valve *c*, which will be approximately proportional to the temperature-deviation, the connections being so arranged that this voltage will be in phase with the anode voltage when the relay is in the open position, as in Fig. 68. The rectified current passed by the control valve will, therefore, be greater than normal, hence the condenser *e* will charge up quickly, causing the relay to close in less than 20 seconds. When the relay closes, however, the contacts *d* are reversed, so that the anode voltage on the control valve will now be out of phase with the grid voltage. As current is only passed by the valve during the half-cycle when the anode is positive, and as during this time the grid will be in the negative half-cycle, the mean rectified current will be less than normal and the condenser *e* will charge slowly, causing the relay to take longer than 20 seconds to open.

Should the temperature of the furnace be high, the out-of-balance voltage will be in opposite phase, and the converse of the preceding will apply.

It will be seen that the control obtained is directly proportional to the deviation of the temperature from normal, so that, provided the time-lag between a change in the mean furnace voltage and the resulting response of the platinum thermometer is less than a certain value, the thermostat will control the temperature without " hunting." Care has to be taken to ensure that the grid and anode voltages on the control valve *c* are as nearly as possible in phase, or antiphase ; and to obtain this, an optimum value of the condenser across the coupling transformer can be determined by trial. For this purpose a cathode-ray oscillograph was used by Prosser. There will also be a certain amount of extraneous pick-up from the mains, and some out-of-phase component, but their effect is to increase the frequency of operation of the relay without appreciably affecting the sensitivity of control.

Alternative circuit.—By a slight modification of the circuit shown in Fig. 68 it is possible to increase the maximum sensitivity about four times, at the same time gaining other advantages. This form of the thermostat was in the experimental stage at the time of writing. The revised control circuit shown in Fig. 69 differs from that of Fig. 68 mainly in that the control valve *c* does not now act as a kind of variable resistance directly in series with the condenser *e*, but is in this case used to supply a variable voltage to charge the condenser *e* through a fixed resistance.

The reason for the change is that it is possible to maintain the grid circuit of the control valve at a constant potential, and there is thus less risk of extraneous pick-up. The control-valve circuit is now less sensitive, but compensation in the form of increased amplification is provided by coupling the low-impedance bridge circuit to the high-impedance amplifier through a microphone-type transformer. A condenser of 0·1 μF, shunted across the secondary

winding brings the output from the amplifier into phase with the anode voltage of the control valve. The stability of the amplifier has been increased by eliminating the condensers across the cathode resistances, thus causing negative feed back to the grids. An additional variable resistance having a logarithmic scale may be inserted in the cathode circuit of the second stage to increase the negative feed back and to control the sensitivity. Owing to the fact that increase of frequency makes the cathode-heater capacity reduce the negative feed back, small condensers are shunted across the anode circuits to guard against parasitic oscillations. As the control valve *c* does not now have its anode-cathode connections reversed when the relay *G* operates, it is

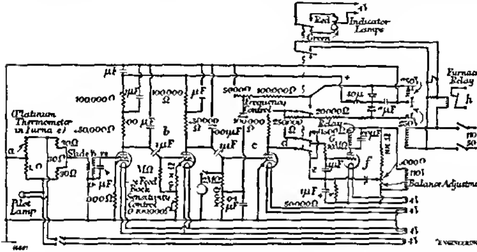

Fig. 69. Modified control circuit in Prosser thermostat

necessary to make separate provision for reversing the phase of the alternating current supply to the anode, or alternatively the phase of the grid voltage may be reversed. This is done by means of an earthed centre-tapped winding on the transformer, using an additional set of contacts on the relay to connect the anode circuit to either end of the winding alternately. The same winding is used to give a full wave rectified supply to the amplifier through two small Westinghouse copper oxide rectifiers. A high resistance shorted between two of the relay contacts maintains the control valve anode voltage when the relay is operating and prevents it from becoming stuck in an intermediate position. A resistance included in one of the transformer leads limits the short circuit current should the relay contact springs be pressed together accidentally.

The normal frequency of operation of the relay can be varied by altering the voltage drop across the anode resistance of the control valve. This is achieved

by altering the grid bias obtained from a small copper-oxide rectifier, tapped across a potentiometer in the anode supply. A similar grid-bias circuit is provided for the relay valve *f*, and is adjusted so that, when the bridge is balanced, the relay will remain in the open and closed positions for equal periods.

It should be possible to provide an additional control proportional to the rate of change of the deviation, hence eliminating hunting in unstable conditions. This could be done conveniently by varying the gain of the amplifier through a suitable control. With a high-gain amplifier it would probably be desirable to use a different frequency from that of the mains for the bridge supply, in which case the control valve could be of a frequency-changer type, with the reference alternating-current voltage applied to an auxiliary grid.

The Cooke and Swallow thermostat.—The resistance type of thermostat designed by Cooke and Swallow[17] also uses the temperature-sensitive resistance in the form of a thermometer in the furnace or bath. The design (Fig. 70) has a number of interesting features to which reference may be made.

The form of the contact make and break is one of these features. Using a Weston relay, it was found that, owing to sticking of the contact-pieces, a considerable current through the coil in the reverse direction is necessary to break contact once it is made. To overcome this difficulty, the moving coil is placed in series with a winding of a telephone transformer. The other winding of the transformer is connected across the mains in series with a 200,000 ohms resistance and a mechanical contact-maker, which makes and quickly breaks contact every 15 sec.

The sudden interruption of current in the winding of the transformer induces a small momentary current in the other winding in series with the relay, giving the pointer a sudden " kick " and pulling it from the contact-piece.

In place of the mechanical contact-breaker, use may be made of the intermittent discharge from a neon lamp[18, 19] when connected across the mains in series with a high resistance of 5 megohms and shunted by a large-capacity condenser of 6 to 8 microfarads.

The contacts of the Weston relay may conveniently be made to operate a triode-valve relay. Fig. 71 illustrates diagrammatically the circuit[20] of the relay used in this thermostat.

L_1 and L_2 are resistances or lamps in series with the filament of the valve, and suitably chosen to give the correct heating current for the filament. If the grid is maintained at the same potential as the filament, anode current will flow through the relay windings to the positive main, sufficiently to operate a post-office relay. By connecting the grid to a point of sufficient negative potential to the filament, this anode current ceases. In the arrangement shown in Fig. 71, the grid is normally maintained at a negative potential of 110 volts with respect to the filament by means of the 5-megohm grid leak connected to the negative main, and no current flows through the relay coil. The Weston

relay contacts are connected to the grid and the negative end of the filament respectively When the Weston relay makes contact, the grid is connected

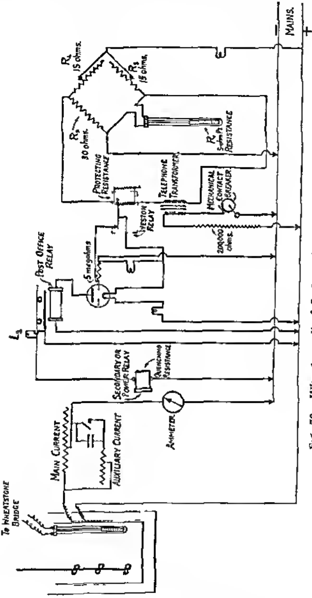

Fig 70 —Wiring circuit of Cooke and Swallow thermostat

directly to the negative end of the filament, bringing it to the same potential as the filament Anode current then flows and operates the post office relay

This arrangement is an extremely sensitive one, a minute movement and pressure of the Weston relay contacts being quite sufficient to operate the post-office relay. To protect the contacts of the post-office relay from damage by excessive sparking, a quenching resistance (Fig. 70) is connected across the windings of a power relay, which is used to cut off the main heating current. Lamp L_3 also minimizes sparking. A rheostat with an " off " position is shunted across the coil of the Weston relay to limit the current passing through it while preliminary adjustments are being made. The Weston relay has to be carefully insulated from vibration to prevent chattering of the contacts.

The use of a resistance thermometer in conjunction with an electron-tube amplifier has been described by Walsh and Milas,[21] and with a thyratron circuit by Zabel and Hancox[22] and also by Henny.[23]

Coates[24] has designed a regulator which does not involve a galvanometer or photocell and does not require accurate phase adjustment.

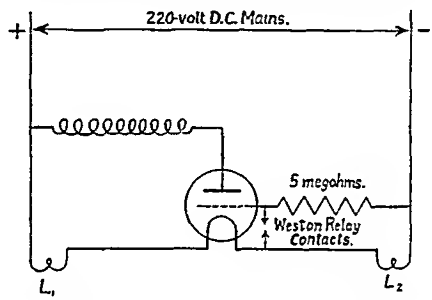

Fig. 71.—Valve-type relay circuit for Cooke and Swallow thermostat (Beaver and Beaver)

The operation of the instrument is based on the reversal of the phase of the out-of-balance e.m.f. of an a.c. bridge which occurs on passing from one side of balance to the other.

The circuit is shown in outline in Fig. 72. Rectifier, smoothing and decoupling circuits are omitted for simplicity. The d.c. anode supply to V_1 and V_3 was provided by a full wave rectifier and smoothing circuit of the type found in domestic a.c. radio receivers. The main circuit consists of three parts, a bridge containing the resistance thermometer, a valve circuit for amplifying the output from the bridge and a controlling device Z. The a.c. bridge consists of a centre-tapped winding of a transformer T_1 giving about 10 v and two resistances R_1 and R_2 ; one of these is the thermometer (of the order of 100Ω or 200Ω) and the other is variable and can be adjusted to balance the bridge at any desired temperature. The transformer T_2 applies an alternating voltage e_{a2} of the order of 300 V, to the anode of V_2, which will pass current only during the half-cycles when e_{a2} is positive. The magnitude of this anode current

depends on the grid voltage e_{g2}, it generates a potential difference across R_3 which is smoothed by C_1, R_4 and C_2 and so applied (e_{g3}) to the grid of V_3

The current i_2 through Z controls the furnace through a suitable relay, and depends on the value of e_{g3}, the circuit is so adjusted that when the bridge is balanced ($e_{g1} = 0$, e_{g3} is constant) the relay or other controlling device included in Z is just about to trip—this adjustment is not critical If the furnace is too cold the bridge is unbalanced and a small voltage $e_{g1} = e^0_{g1} \sin pt$ is impressed on the grid of V_1, this is amplified by V_1 and appears at the grid of V_2 as a much larger voltage $e_{g2} = me^0_{g1} \sin(pt + \pi)$ where m is the voltage amplification of V_1 and its associated circuit This voltage, being of opposite phase to the anode voltage of $V_2 (e_{a2} = e^0_{a2} \sin pt)$, will decrease the anode current i_2 of this tube consequently the negative grid bias e_{g3} on V_3 will decrease and the current through the controller will increase If the furnace now becomes too hot, the bridge again becomes unbalanced and a small voltage $e_{g1} = e^0_{g1}$

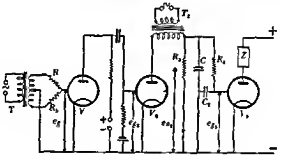

Fig 72 —Circuit of a wide range thermoregulator

$\sin(pt + \pi)$ is impressed on the grid of V_1, the grid voltage of V_2 is now $e_{g2} = me^0_{g1} \sin pt$ i_2 increases as e_{g2} is in phase with e_a e_{g3} becomes more negative and the current through the controller decreases The operation of the circuit will be made clear by reference to Fig 73 and the following table, which shows the conditions obtaining under the three possible states —

Furnace cold	Balance	Furnace hot
$e^0_{g1} \sin pt$	0	$e^0_{g1} \sin(pt + \pi)$
$me^0_{g1} \sin(pt + \pi)$	0	$me^0_{g1} \sin pt$
$e^0_{a2} \sin pt$	$e^0_{a2} \sin pt$	$e^0_{a2} \sin pt$
Decreased	Mean value	Increased
Increased	Relay about to trip	Decreased

On account of the high input impedance of V_1 at low frequencies the sensitivity of the instrument can be considerably increased by the insertion of a high ratio (e g microphone) transformer between the output of the resistance thermometer bridge and the grid of V_1

The instrument is easy to make, most of the parts required being ordinary radio receiver components. The sensitivity can be increased simply by increasing the a.c. amplification between e_{g1} and e_{g2}, i.e. V_1 may consist of an amplifier containing as many valves as the required sensitivity demands.

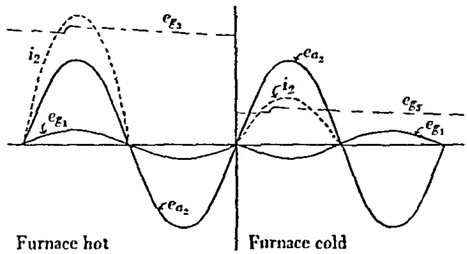

Fig. 73.—Operation of thermoregulator

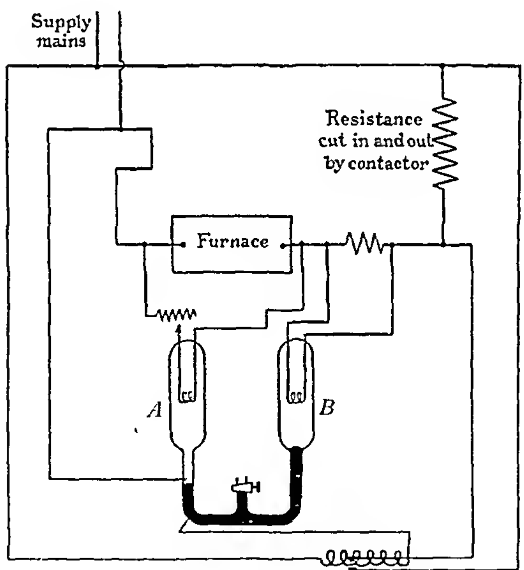

Fig. 74.—Principle of the Proctor and Douglas temperature-regulator

The thermometer consisted of 33 ft. of 40 s.w.g. platinum wire, and the relay Z was a Sunvic vacuum switch. The sensitivity was sufficient to control a (paraffin) thermostat to $\pm$ 0·001° C at $-$ 20° C. A valuable feature of the

circuit is the very small effect of mains voltage variations, with suitable adjustments to the automatic grid bias or other parts of the circuit the effect of mains variations can be made quite negligible. Initial adjustments are not critical, but reasonably non inductive resistances should be used for the bridge circuit.

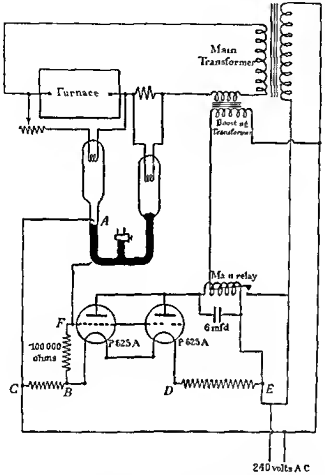

Fig 75.—Proctor and Douglas regulator circuit using valve relay

The bridge need not be exactly in balance at the desired operating temperature, and experiment has shown that the regulator does not fail when the bridge is very highly out of balance though the anode current of the last valve may have to be limited in some way. Small phase displacements occurring in any of the valve circuits do not affect the operation appreciably.

Utilization of the resistance-current-voltage relationship as a means of control

If the temperature of an electrical-resistance furnace rises and the resistance increases, the ratio of the current flowing through the furnace to the voltage across it will decrease. This effect has been made use of by R. Proctor and R. Douglas[25] in a simple control device.

The principle of the regulator is shown diagrammatically in Fig. 74. *A* and *B* are two glass bulbs filled with air at atmospheric pressure, and connected together by a mercury manometer. Mounted in each of the bulbs is a heater filament. The filament in the bulb *A* is connected so as to be heated in proportion to the voltage across the furnace, while the filament in bulb *B* is heated in proportion to the current flowing through the furnace, as shown in Fig. 74. If the temperature of the furnace rises and the resistance increases, the ratio of the current flowing through the furnace to the voltage across will decrease. As a result the current passing through the coil enclosed in *A* will increase relative to that flowing through the coil in *B* and thus cause the air pressure in *A* to increase compared with that in *B*. This will cause the mercury in the manometer to fall in the left limb, breaking the relay current and reducing the power supplied to the furnace by inserting a resistance in series with the furnace. The regulator is equally applicable to a furnace having a negative temperature-coefficient by interchanging the voltage and current connections of the two bulbs. To avoid fouling of the mercury contacts, it is advisable to use a thermionic-valve relay, as shown in Fig. 75.

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HAPTER 13

Indicator and recorder pointer types of regulator

CONTACT TYPES

THE contact type of regulator is used both in the laboratory and in industry Temperature indicators and recorders have a pointer attached to the galvanometer if the pyrometer is of the thermo-electric or resistance type, and a pointer attached to the Bourdon-tube gauge if of the liquid-expansion or vapour-pressure type The movement of these pointers can be utilized to control temperature The pointers have, however, very little mechanical power behind them , indeed, the galvanometer pointer has practically none In general, adjustable contacts are arranged on either side of the pointer at the desired temperature, and deviation of the pointer from this value will cause the closing of one or other of the contacts This may be done either directly or with the aid of an auxiliary mechanism

Direct closing of the contacts is possible with the Bourdon tube gauge type, since there is a small amount of power available In this case the pointer carries contacts, but with a galvanometer movement an auxiliary form of power is necessary The galvanometer movement then only performs the function of determining which contact shall be closed by the auxiliary mechanism One contact is used for closing the main circuit when the temperature falls below the value determined by its position, whilst the other contact similarly switches off the current when the temperature determined by its position is exceeded The main circuit is usually operated through the medium of a relay

The Gouy principle can be applied to the thermoelectric form of instrument by adding an oscillating voltage to the thermocouple voltage This is produced by passing a small current through a resistance periodically varied from 0 to 10 ohms by the movement of mercury over the resistance The resistance and mercury are contained in a U-tube which is oscillated at 9 cycles or so per minute For maximum effectiveness the oscillating voltage should only be 10 to 20 per cent greater than the dead zone of the contacting galvanometer

An example of the type of instrument in which the contact is closed directly by the movement of the pointer is shown in Fig 76 The two indexes can be set at a distance apart, so that the temperature can fluctuate within a range The contact arms, carried on the two indexes, are pivoted and controlled by a

spring in such a way that the pointer is able to continue its passage across the scale, above or below the points at which contact is made, and indicate the temperature approximately. The spring serves to restore the contact arm to its original position on release.

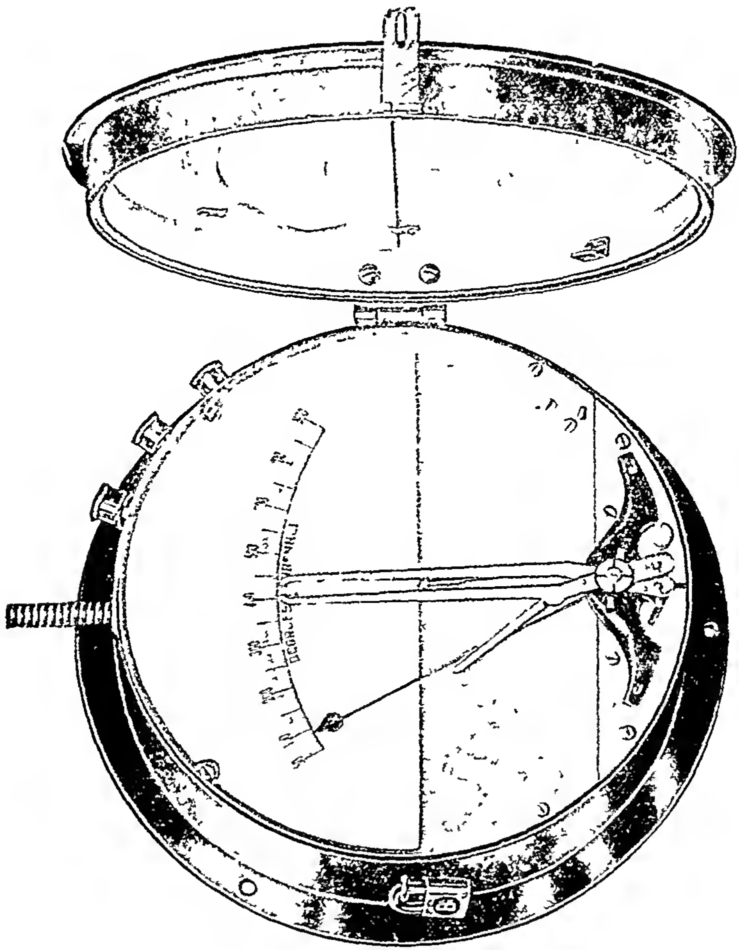


Fig. 76.—Brown control thermometer

A novel contact device in one form of *Drayton* regulator is a small magnet attached to the fixed contact, so that when the moving contact comes within its field it is attracted and makes firm contact. The circuit is broken with snap action, thus minimizing sparking. This device naturally introduces

some lag at the controlled temperature, but nevertheless ensures positive make and break

"Chopper-bar" type

In this system an auxiliary mechanism closes the contacts Two pairs of contacts may be mounted on one table which can be set at any point along the scale, or each pair may be mounted separately and adjusted independently (see Fig 77) At definite intervals a "chopper-bar," actuated by clockwork, electric motor, or an electro-magnet, depresses the temperature indicating pointer and, depending on the position of the pointer, closes either the

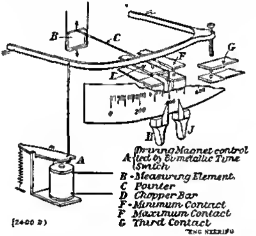


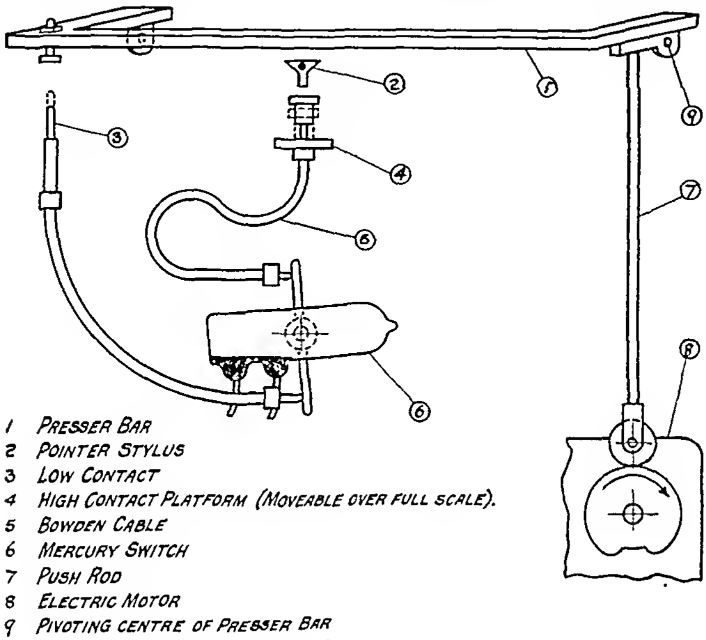
Fig 77—Schematic diagram of chopper bar temperature regulator

"high" or "low" contacts In addition to temperature indication on the scale and, if desired also on a chart, a visual indicator in the form of red, green and white lights can be arranged to show when the upper, lower, or predetermined temperature has been reached The ' chopper bar" type possesses the advantage of permitting free movement of the pointer, except at the short intervals of contact The instrument can be designed so that the temperatures at two points may be controlled by a switching mechanism which connects two thermocouples alternately to the control instrument The instrument is fitted in this case with two contact devices Another possibility is that two furnaces can be maintained at the same temperature by a similar switching arrangement with the assistance of two relays, one for each furnace

Instead of using contact tables, a mechanical movement may be used at this point of the instrument, as in the " Flexipush " arrangement of the Foster Instrument Co illustrated in Fig 78 The downward movement of the chopper-

or presser-bar depresses one or other of two tables, depending on the temperature. These tables are linked, by Bowden flexible cables, to the respective ends of the pivoted support of a mercury switch.

The instrument made by Electro Meters, Ltd., employs a somewhat different arrangement (illustrated in Fig. 79) of the auxiliary mechanism to translate the movements of the pointer into a means of control. The index 1 is set to the temperature at which it is desired to maintain the furnace. The pyrometer consists of a milli-voltmeter with a magnet system 2 and indicating



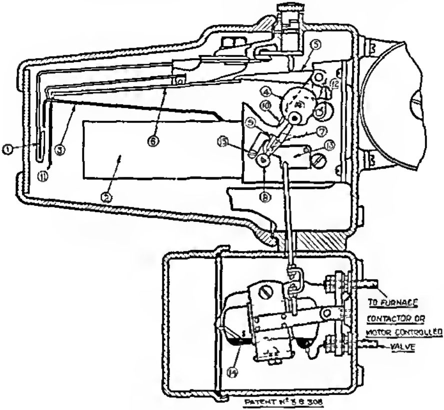
Foster Instrument Co., Ltd.

Fig. 78.—Operating diagram of "Flexipush" controller

pointer 3. A shaft driven through worm gearing from the motor on the back of the indicator rotates a cam 4 which, through the bell-crank lever 5, causes a control arm 6 to be raised and depressed periodically. This cam also acts as a switch-lifting crank, imparting a reciprocating motion to the connecting-rod 7 and pin 8. This pin traverses one of two paths in the slot 9, determined by the extreme angular position of the selector arm 10, and throws the switch "On" or "Off."

Suppose the furnace cold and ready to be started-up. The indicating pointer 3 will be below the index 1. The control arm 6, on its downward stroke,

will be free to fall behind the scale plate 11, lifting the bell-crank lever 5 and, through the roller 12, raising the selector arm 10 The pin 8 thus traverses the lower path in the slot 9, catches the trigger 13, and lifts the mercury switch 14 to the "On" position The switch itself is held in position by a pawl 15, closing the circuit This switch can be arranged in series with a circuit breaker, motor controlled valves, dampers, or similar gear, and maintains a supply



[Electro Meters Ltd

Fig 79—Electro Meters regulator

of heat to the furnace until the indicating pointer 3 rises just beyond the control index 1 The downward motion of the control arm 6 is now intercepted by the indicating pointer 3, with the result that the selector arm 10 is allowed to fall back, causing the pin 8 to follow the upper path in the slot 9 The pin catches the pawl 15 and, releasing the trigger 13, throws the switch "Off" The circuit is broken and the supply of heat to the furnace is interrupted until the pointer again falls below the control index, when the cycle of operations is repeated

Regulators of the contact type with galvanometer indicators can be arranged

to control rates of heating or cooling. This can be done by suitable movement of the contacts by mechanical means.

An alternative method is to leave the control contacts stationary and introduce an additional electromotive force into the thermocouple circuit.

The advantage of the latter method is that it may be added to any existing automatic-control installation ; but its disadvantage is that the readings of the control pyrometer are falsified. An index could, however, be arranged to indicate the amount of additional e.m f.

NON-CONTACT TYPES

The movement of the galvanometer coil is made use of in a number of non-contact types of control instrument. The object of the design is to avoid causing the galvanometer to perform work or subjecting it to restraint.

Pointer-thermocouple type

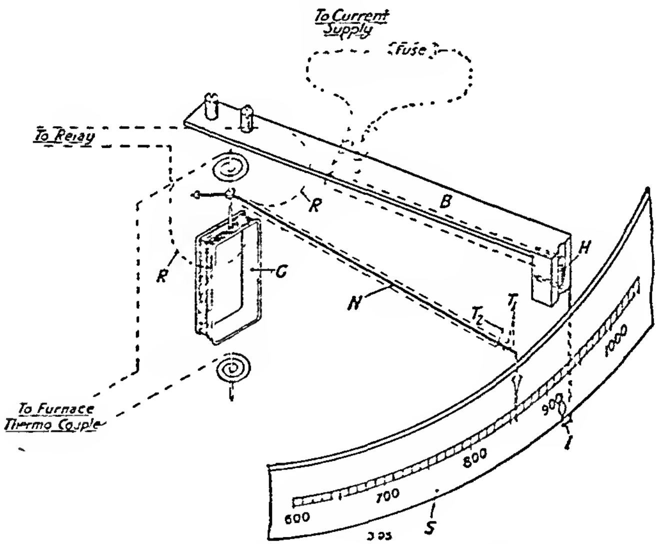


Fig. 80.—Cambridge Pointer-thermocouple regulator

A Cambridge pointer-thermocouple instrument is of this class. The manufacture of this instrument is now discontinued, but a description is, nevertheless, included because of its intrinsic interest as a method which has been found serviceable, and there are instruments of this type still in use.

The galvanometer movement is illustrated in the diagram, Fig. 80. The pointer N, attached to the pivoted moving coil G, carries at its extremity a

differential thermocouple T_1, T_2, which is connected electrically to a moving coil relay. A small electrically heated coil or "heater," H, is mounted on the movable arm B, which is set, by means of a handle, to the point on the scale at which it is desired to control the temperature, an index I being provided to indicate the setting. When the required temperature is nearly reached, the thermocouple T_1 arrives opposite the heater, and an electromotive force is set up which tends for the moment to throw the relay arm away from the contact which it will eventually close. As the temperature in the furnace (or other heated body being controlled) still increases, the pointer N continues to move along the scale until the second thermocouple T_2 is opposite the heater. The electromotive force then generated actuates the relay, closing an electrical circuit which operates a mechanism controlling the supply of heat. Owing to the mass of the furnace, the temperature will probably continue to rise, even though the heat supply is reduced, and the pointer will continue to move up the scale until it meets a stop (not shown in the diagram) where it remains until the temperature falls. As the furnace cools, the pointer N moves down the scale, and when the thermocouple T_1 comes in front of the heater the electromotive force again generated causes the relay to break contact (in case, by any mischance, the contact is sticking), and the supply of heat is thus increased. The pointer N is fitted with an index, so that its position can be seen on the scale, but it will be appreciated that if the temperature exceeds the required value the pointer will not indicate it, owing to the stop. A mirror is usually fitted behind the scale to avoid parallax errors. The heater can be set and the regulator arranged to control the temperature, at any point between the upper and lower limits of the scale, or the regulator can be fitted with a time temperature device as described later. To prevent the regulator failing to function owing to an interruption in the supply of current to the heater a safety device is provided whereby the supply of heat to the process being controlled is shut off automatically if the heater circuit should be broken. Alternatively, this device can be adapted to sound an alarm bell or to operate a light or other signal.

The energy consumed by the heater circuit is approximately two watts, and the instrument can be operated from a d c or a c supply by connecting a suitable resistance or a transformer in the circuit. If an electrical supply mains is not available, the instrument can be operated from a 4 volt accumulator. The regulator can be used in conjunction with a resistance thermometer, thermocouple or radiation pyrometer, the type of element selected depending upon the application for which the outfit is required. When used in conjunction with an electrical resistance thermometer the scale of the regulator is calibrated to cover only a few degrees above and below the critical temperature, thus securing a very open scale.

Electronic

In a Wheelco instrument the galvanometer pointer carries a very light aluminium vane. Motion of the pointer will carry the vane between two minute coils which are connected to an oscillating circuit. The motion changes the inductance of the coils sufficiently to change the frequency of the oscillator and operate a relay.

Adcock has described a method of controlling the rate of heating and cooling of laboratory resistance furnaces by the use of a moving potential divider which provides a steadily increasing or decreasing e m f The latter is opposed to the e m.f. due to a controlling thermocouple in the furnace and the resulting small current deflects a mirror galvanometer which operates a photocell in conjunction with a thyratron and electric motor to regulate the furnace heating current.

In the Tinsley Amplifier Controller which is of the proportional-floating reset type, the e m f. of a thermocouple is amplified by thermionic means and fed to a magnetic movement that operates an oil servo motor which in turn controls two other oil servo motors. The operation of the first oil servo motor is influenced by an elastic reset mechanism and the shaft that is operated by the last of the oil servo motors alters at least one of the factors which influence the control value that operates the whole mechanism which is without a stabilisation point of its own.

The resetting mechanism which influences the first of the mechanical amplifiers alters the amount of energy that has to be supplied by the electronic part of the Controller in relation to the controlled e.m f to keep the link between the electrical and mechanical parts of the Controller in balance.

It is possible to separate the amplifying parts from the mechanical parts of the controller and connect them by means of a cable and it is further possible to put any necessary distance between the detector and the amplifying parts of the controller.

Method of operation —The electrical voltage generated by the thermocouple *a* is applied to a reflecting galvanometer *b* (Fig 81) in series with a standard resistance *c*. Light from a lamp *d* is reflected by the galvanometer on to a photocell *e*, which in turn controls the magnitude and phase upon the grid of a thermionic valve *f*, in such a way that the grid voltage shifts in proportion to the degree of illumination of the photocell The thermionic valve becomes conductive when the grid voltage reaches a certain potential and remains so for the rest of the positive half cycle. thus as the phase of the grid advances the duration of the conducting period increases giving a larger effective rectified output of the amplification part. Thus, the effective output current is controlled by the degree of illumination of the photocell and by the deflection of the galvanometer.

The current output is fed back through the standard resistance *c* in such a way that the voltage drop due to it opposes the original voltage. Thus when

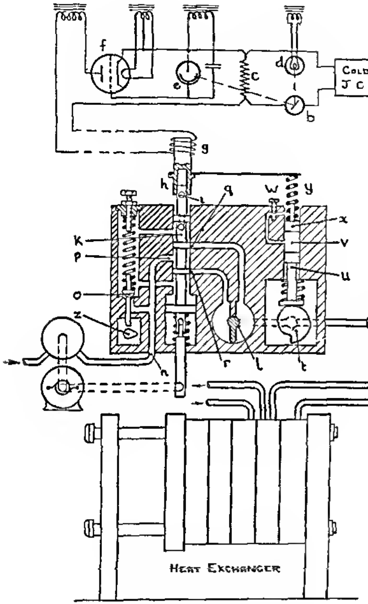


Fig 81 —Tinsley amplifier controller

the input e.m.f. rises, causing the galvanometer *b* to deflect, the voltage drop on the standard resistance *c* rises until the input voltage is balanced. This gives proportional amplification independent of the external output circuit. Smoothing condensers and inductors are used to convert the unidirectional current pulses into a smooth direct current. This output is fed to a magnetic solenoid *g* which operates the first oil servo motor *h*. The opening and closing of the hole *i* of this servo motor operates the two servo motors *k* and *l* by causing the oil pressure applied to them to become unbalanced. A reduced oil pressure is applied through the inlet *n* via the reducing valve *o*; the full oil pressure is applied directly to the common chamber *p*.

The oil pump and driving motor are shown separately in Fig. 81 for clarity, but in fact they are incorporated in the main casing.

If the operation of the electro-magnetic solenoid causes the solenoid *g* to rise, opening the hole *i*, the power applied to the top of servo motor *k* falls below the power applied from the bottom plus the effect of the spring supporting *k* and the piston rises opening port *q* to the full pressure and port *r* to the reduced pressure. These two pressures are applied to the last servo motor *l* causing it to rotate in a clockwise direction and to operate the controlling valve *s*. At the same time the cam *t* is rotated in the same direction causing the piston *u* to fall under the influence of its spring. Oil is fed into the cylinder *v* so that with the bleed screw *w* partly closed the piston *x* follows the movement of the piston *u* exerting a downward pressure on the first servo motor *h* through spring *y*. The strength of this spring determines the angle through which the servo motor *l* moves before balance is re-established after a deviation and the bleed screw *w* will determine the time constant of the reset (300°/second to 300°/hour).

Thus on a variation in output of the amplification part of the controller, the controlling valve immediately actuates to some proportional position to correct the deviation in the controlled temperature. The amount of this proportional correcting is controlled by the strength of the spring. After the initial operation a state of affairs is achieved in which the control point is temporarily shifted (reset) in such a way as if the deviation from the correct value was already corrected. For the time being the balance is re-established by the additional force exerted by spring *y*; but, the alteration of the valve position begins slowly to have effect and in a similar manner the power exerted by the spring *y* is slowly reduced since oil is passing by the bleed screw *w* according to its setting, which has the effect to make the piston *x* more and more independent of the position of the valve *s* and of the piston *u*. The bleed screw *w* is set according to the time constant of the controlled apparatus. In that way the amount of reset exerted by the spring *y* is diminishing continuously and is exactly equal and opposite to the difference between the temperature that is actually measured during this period of transition and the final temperature

to which the position of the valve is bringing the system eventually if it is given enough time This balance is kept until the full effect of the new valve position is achieved and at that time no resetting force is exerted because the oil passing through the leak has equalized pressure on both sides of the piston

The controller, therefore, takes up a new valve position appropriate to the deviation in one operation

The process described here takes account of only one alteration of the temperature, for instance, a variation, from 163° to 165° F by a constant increase of the steam temperature that is not altered until the new balanced position is reached In reality the controlled temperature is, of course, subject to many factors that all change continuously

When the physical magnitudes are being controlled by the measurement of voltages generated by thermocouples, a cold junction compensation is incorporated by means of a bridge circuit, one arm of which is a resistance thermometer Variations in the ambient temperature cause the bridge to become unbalanced and the out of balance e m f is arranged to compensate for changes in thermocouple e m f's

Reference

(1) ADCOCK *J Sci Instr* 1935 **12** 285

CHAPTER 14

Potentiometric regulators

POTENTIOMETER regulators are closely allied to the indicator or recorder contact types of regulators. Instead of a simple galvanometer to measure the e.m.f. developed by the thermocouple, the e.m.f. is balanced by means of a potentiometer circuit, a galvanometer indicating any momentary out-of-balance voltage.

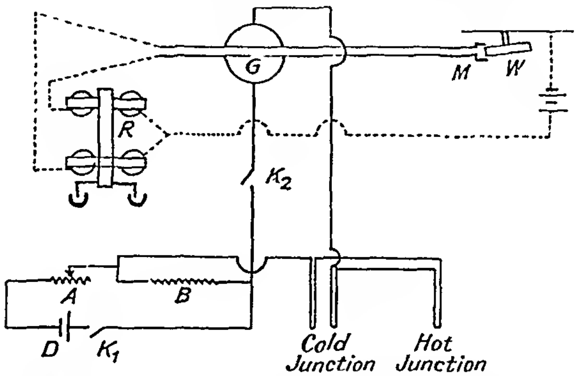


Fig. 82.—Electrical connections of Stockdale thermostat

A number of forms of potentiometric regulators are available. These instruments are robust and accurate and are used both in the laboratory and industrially. They may be used in conjunction with a thermocouple, resistance thermometer, or certain radiation pyrometers. Normally they are arranged to work upon the potentiometric principle, but when used with electrical-resistance thermometers they are connected in some form of Wheatstone bridge.

Before dealing with the industrial forms of instrument, a laboratory type will first be referred to.

Stockdale's design of instrument[1], is shown diagrammatically in Fig. 82. The thermocouple is balanced by a potentiometer circuit, *D* being the cell, *A* the slide wire, *B* a fixed resistance, and *G* the galvanometer to indicate balance or out-of-balance conditions. The interesting feature of the instrument is the control of temperature by the galvanometer contact. The coil of the galvanometer *G* carries a double boom *M*, the two parts of which are insulated from each other. The ends of the boom are of platinum and are so bent as to lie

closely on either side of a platinum rimmed wheel W If the boom moves one or other of the prongs will touch the wheel closing a 4 volt circuit and actuating a double relay R Two resistances in parallel are arranged in series with the furnace and the relay is in series with one of these resistances when this resistance is taken out of the circuit by the relay the current to the furnace is decreased The wheel W is made to have a cant of 12 degrees and is driven by clockwork at a speed of one revolution per minute to make the action more

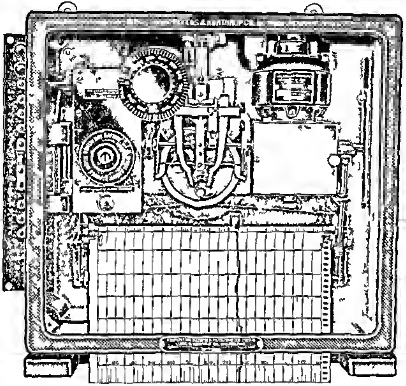


Fig 83 —Leeds and Northrup potentiometer recorder controller (original design)

lively The prongs are placed so close that the slightest movement makes contact Each prong normally touches the contact wheel for 30 seconds and therefore the high and low currents are on for the same time when the temperature is correct

The relay is sometimes troublesome because perfect contact between the wheel and prongs is difficult to obtain and consequently the current actuating the magnets is intermittent Adjustment has to be made so that the slightest impulse sends the arm either one way or the other If the arm moves too freely however it will rebound off the wheel This difficulty may be largely overcome

by increasing the moment of inertia of the arm, but a better method, involving a little more complication, would be to use a triode-valve relay, and so decrease the contact and current necessary to actuate the circuit.

Industrial potentiometric controllers

We turn now to the industrial type of potentiometer regulators. An important feature of these is the method of mechanically balancing the circuit. As an example of the principles of the method employed, the original design of the Leeds and Northrup instrument (Fig. 83) will be described. Subsequent modifications in detail have been made, which will be referred to later.

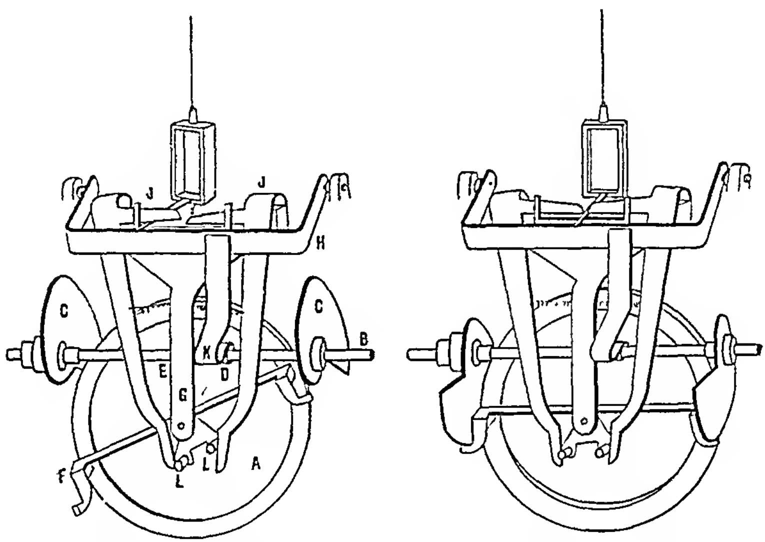
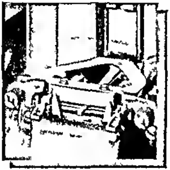


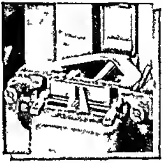
Fig. 84.—Principle of Leeds and Northrup recording potentiometer (original design)

The action is as follows: The disc *A* (Fig. 84) is mounted on a shaft and operates the slide-wire contact by a cord wound on a circumference visible in the figure. The power is supplied by a small, continuously-running motor and enters the mechanical system through the shaft *B* carrying the large cams *C* and the small cams *D* and *E* (*E* being behind *G* in the diagram). At each revolution of the shaft *B*, the cams *C* straighten out the arm *F*, which perchance has been tilted a moment before, and in doing this will rotate the disc *A*, arm *F* being pressed at this time against the disc *A* by the spring *G*. The arm *F* engages in serrations on *A* which prevent slipping. The arm *F* is pivoted on the spring *G*, which is fast to the frame of the instrument. When the cams *C* have rotated until their longest radii are passing the extension of the arm *F*,

the cam E begins to raise G, lifting F away from the disc When F is free the cam D raises through K the rocker arm H which, in case the galvanometer is unbalanced catches the pointer under one of the pivoted right angle levers J One lever is thus made to swing the arm F by pressing against one of the con centrically situated lugs L The rocker arm H is then immediately lowered to allow the galvanometer to swing freely Cam E is so shaped and fixed on the shaft B that it will recede from the spring G, allowing G to press F against the disc just before the cams C begin once more to straighten F



(a)



(b)

(c)

Details of balancing device

(a) Here temperature at thermocouple is constant therefore circuit is balanced and pointer at centre Pointer is now unclamped and feelers open

(b) Temperature is still constant Cushion clamp gripped pointer Feelers then closed on it and found it in balanced position Clutch stationary temperature record constant

(c) Temperature has changed Clamp grips pointer and feelers close on it in unbalanced position Clutch arm is moved to position grips disc and cams move sideways and pen to new position

Fig 85—Leeds and Northrup Micromax arrangement

The disc A moves the contact on the slide wire The shaft B rotates once in about 2 seconds which is slow enough to allow the galvanometer time to come to rest, or nearly so The design is such that the amount of rotation of the arm F increases with the extent of the galvanometer deflection since the pointer approaches the fulcrum of the levers J as the deflection increases The motion of H is adjusted so that the rotation of F will correspond to a re balancing step of the pen of $\frac{3}{4}$ in (19 mm) when the deflection is a maximum decreasing uniformly to about $\frac{1}{50}$ in when the deflection is just sufficient to catch the boom under one of the right angle levers This gives sufficient

rapidity of the various actions to take the pen the width of the scale in somewhat less than one minute. The position of the pen, when a balance has been obtained just before each record, corresponds to a definite point on the slide-wire, for the pen is fixed to the slide-wire contact. Periodically the thermocouple is disconnected and the standard cell connection automatically made. At the same time the potentiometer slide-wire is set free from its shaft and the clutch engages a second resistance. Movements of the disc then result in changing the resistance of the battery circuit, and the current is thus set to its proper value. The pen does not follow this adjustment and no record is made of variations in the current. A short-circuiting contact on the slide-wire carries the pen to zero on the chart when the battery is run down, thus providing ample warning in most circumstances.

In most of the recent designs of potentiometer recorders the "follow-up" mechanism to move the slide-wire contact is of the scissors pattern. The galvanometer needle is clamped by a cam-operated bar, and whilst held in this position a scissor mechanism closes on it. A clutch is engaged and, being linked with the scissors, rotates the main spindle by an amount proportionate to the deviation picked up by the scissors from the galvanometer needle (see Fig. 85).

Temperature-control in potentiometric regulators

The control mechanism used in conjunction with the potentiometer types which have been described consists, in general, of a mechanism attached to the same shaft as the disc, and in such a way that when it rotates, contacts are operated. Cam and disc mechanisms are the two alternatives, and the choice between these depends upon the nature of the process to be controlled. Cam-operated control is now, however, little used, as with the gradual slope of the cam it is not possible to produce the necessary rapid make and break of the contacts, the gradual movement resulting in a hesitant make-and-break action.

Disc-operated mechanism.—With the disc-operated type of mechanism (Fig. 86) the inner and outer radial surfaces of a flange are used to hold the contact open or closed. "Raise" and "Lower" contacts are operated by separate discs, and contact is made or broken with a "snap" action, according to the direction of rotation of the main slide-wire spindle. Either two- or three-position control is possible. The two-position control (Fig. 86) is of the "on and off" type, and in this form the valve or contractor is either in the fully open or shut position. An adjustable by-pass is usually provided with this type of control on fuel-fired furnaces. Two-position control is suitable for furnaces with constant loading conditions.

In three-position control, additional contacts are provided on the instrument and on the motorized valve. Normally the control operates between the intermediate switches. If, however, changes in loading cause a large rise or fall in temperature, the corresponding outer contact is made and the valve is moved to

a greater extent in the closing or opening direction This form of control is particularly suited for furnaces requiring a rapid heat up followed by a "soaking period

Cambridge non recorder controller—In this (see Fig 87) the circuit is controlled by a mercury in glass tilting switch A similar arrangement of control mechanism is used to that of the original Leeds and Northrup design, with certain modifications The galvanometer pointer swings horizontally

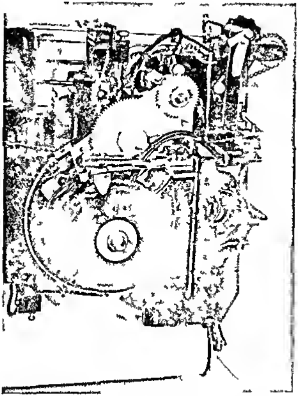


Fig 86—Kent on off control mechanism

below two bell crank levers and above a clamping jaw or chopper bar which is periodically raised thus clamping the pointer against one or other of the levers Hinged to the clamping jaw is a long tail rod passing through a guide hole This tail piece is deflected to one side or the other by the lower arm of one of the bell crank levers if the galvanometer needle is not at zero in the centre When the clamping bar and tail rod drop the bottom end of the tail rod will tilt a mercury switch in one direction or the other depending on the way in which the rod has been deflected previously

Normally the mercury switch is provided with two positions only, i.e. with the contacts either made or broken. If desired, however, a two-way tube

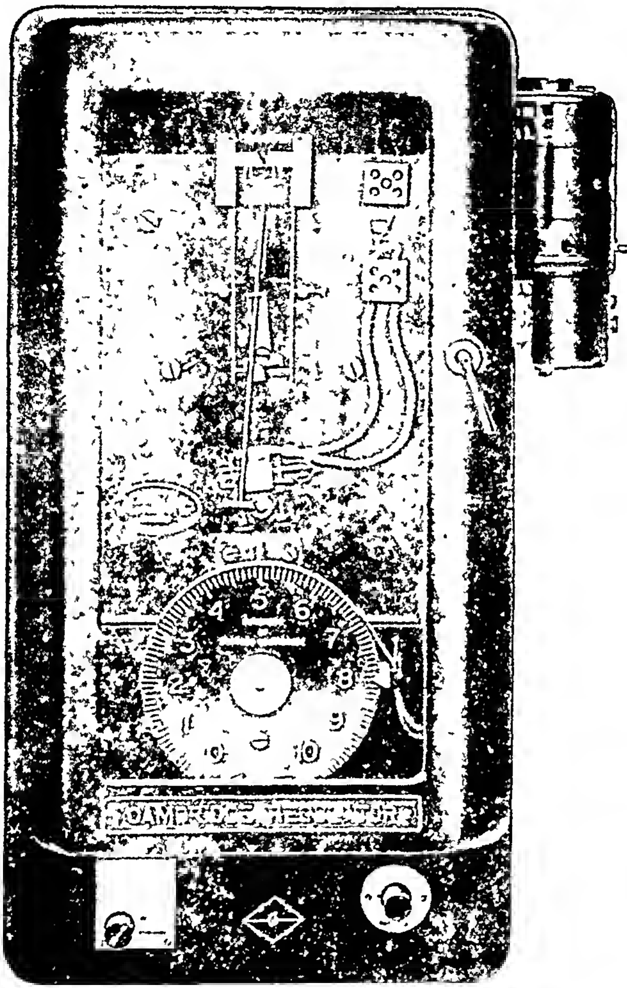


Fig. 87.—Cambridge potentiometer controller

with a common centre contact may be fitted, which will close one circuit when the temperature is too low, and close another circuit when it is too high, both circuits being open when the temperature is correct.

Mercury-tilting switches are also used in the Cambridge recording controller The action can be described briefly as follows The scissors action, already described, rotates a disc which has cam-shaped slots cut in it Depending on the position of the disc, and therefore of the slots, a mercury switch will be tilted one way or the other The pivoted holder of the switch has two small vertical projections, one at each end, and one of these may be immediately beneath either a plain or slotted portion of the disc as it descends after the balancing action

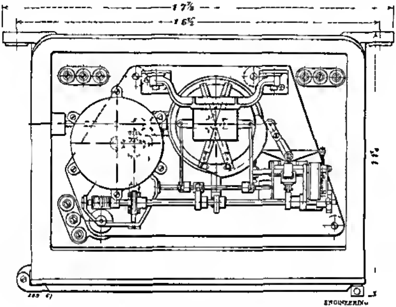


Fig 88 —General plan of Kent controller and recorder

Rate of deviation

In some controllers, account is taken not only of the actual deviation from the required temperature, but also the rate of deviation A relatively large adjustment is made when the deviation and rate of deviation are of the same sign, a very much reduced adjustment, no adjustment at all, or even an adjustment in the opposite sense being made when the deviation and the rate of deviation are of opposite signs, as they are when the temperature is returning to the required value after a deviation

The instrument designed with this purpose in view by Hodgson and made by Messrs George Kent is illustrated in Figs 88-90 A thermocouple is connected to a moving coil galvanometer in the instrument The deviation and rate of deviation from the desired temperature are measured at intervals of 20 seconds by a mechanism driven by a constant-speed motor This mechanism

is shown in plan in Fig. 88. The galvanometer needle, not shown in the figure, is situated between the top of a drum and a metal disc extending slightly beyond them, and is firmly clamped between these parts each time the mechanism operates. The normal position of the pointer coincides with the vertical centre-line in Fig. 88, but if any change of temperature has occurred, it will move to one side or the other when released. The two bell-crank levers shown are rotated by the mechanism so that their lower ends close together on to the end of the galvanometer needle, which is by then clamped, and if any deflection has taken place while the needle was free, the drum will be rotated by the pressure exerted on the end of the galvanometer needle. Attached to the drum and rotating with it is a potentiometer slide wire, which moves against a fixed contact, the motion (produced as already explained) continuing in steps until the balance has been restored, when the galvanometer needle will remain in the central position. The total movement of the drum is, therefore, proportional to the change in temperature. The drum is also fitted with a cam of the form shown in Fig. 88, and a roller arm bearing on this cam controls the opening and closing of two contacts which, in turn, control the flow of current to two solenoids. The latter open or close a throttle valve in the fuel-supply pipe to the plant, by mechanism which will be referred to later. The position of the valve is thus dependent on the temperature-deviation from the normal.

The same solenoids are also controlled by two other contacts, the opening and closing of which is dependent on the rate at which a temperature-deviation takes place. These contacts are carried on the ends of the bell-crank levers which close on to the end of the galvanometer needle, as already explained (Fig. 88). It will be evident that which of these contacts is closed will depend upon the direction in which the galvanometer needle has been deflected, i.e. upon whether the temperature is rising or falling ; and the length of time for which either of the contacts is closed will depend upon the extent of the deflection, i.e. upon whether the change in either direction is taking place rapidly or slowly. It may here be mentioned that although the electrical circuits are made by the contacts referred to, they are often broken by mercury switches, so that damage to the contacts by sparking is avoided.

One of the two solenoids is shown overleaf in Fig. 89 and both can be seen in Fig. 90. As will be clear from the former, the plunger of each solenoid is connected to a pivoted frame in which is mounted a spindle, fitted with a worm wheel near its upper end. When one of the solenoids is energized, its frame is pulled over so that the worm wheel engages with a worm on a horizontal shaft, which is driven continuously at a high speed by a small electric motor. The engagement takes place positively and instantaneously without any shock. When one or other of the worm wheels is engaged, the control valve is opened or closed by a train of gears, crank arms and links, as will be clear from Figs. 88 to 90. A differential gear is included, so that if both worm wheels are engaged

simultaneously, no movement of the valve takes place ; and provision is made for the controls to be inoperative when the valve is opened to a predetermined

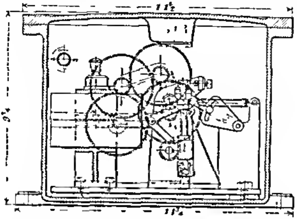
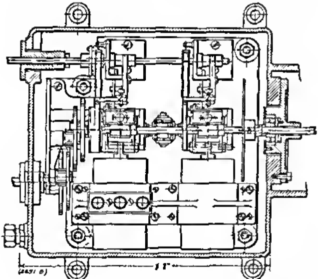


Fig 89 —Sectional elevation of Kent controller and recorder



ENGINEERING

Fig 90.—Plan of Kent controller and recorder
Showing the two solenoids and connections with control valve

extent and when it is fully shut Push-button control, which overrides the automatic control, is also provided

To minimize "hunting" the Deoscillator of the Foxboro' Company imparts into the thermocouple circuit an additional electromotive force (in either

the positive or negative direction as may be required), so as to deflect the galvanometer of the control pyrometer slightly beyond the position it would register in relation to the actual thermocouple temperature at the moment.

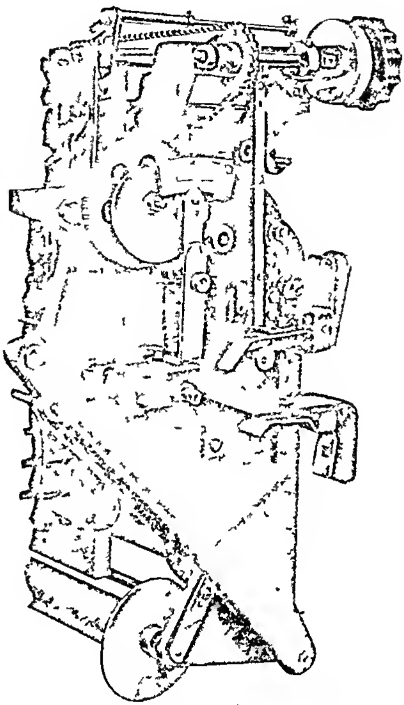


Fig. 91.—Kent floating control (Present design)

The same cam discs and control setting scale are used as for "on-off" control, but an interrupter mechanism is added which breaks the control signal for part of its duration This can be adjusted to vary the proportion of make and break

This type of control is best suited to continuous plants where loads are fairly constant, or load changes gradual The heating capacity should be ample to insure quick response to changes in valve position

The control valves are "floated to the position required to give the correct fuel rate for constant temperature in the plant The valve moves in fixed steps, and may be adjusted manually to suit conditions The primary control contacts have an adjustable zone or differential so that the valve will remain stationary when the fuel rate is correct

The temperature indication is therefore distorted at the moments when the anticipating action is taking place. The anticipatory action is adjustable, that is, the temperature below or above the desired control temperature at which the heat input is decreased or increased, respectively, can be chosen.

An interesting contact type of two position proportional controller has been described by Abbott[*] The arrangement consists of two contact making galvanometers in conjunction with Post Office type relays to form an oscillating system

The instrument differs from the conventional two position controller in its ability to switch on and off without changes of temperature taking place and in being capable of proportioning the 'on' to 'off' time in relation to the position of the controlled temperature within a definite zone.

It is useful for control of electrically heated apparatus on applications where there is considerable thermal inertia and delayed response at the thermocouple to changes of heat input, that is, where proportional control is needed but where the heating medium is not readily amenable to throttling

The instrument may be considered as having two distinct divisions In one there is an oscillating system comprising two sensitive, contact making galvanometers connected to relays as shown in Fig 92 The other division consists of a conventional potentiometer bridge and thermocouple

The novel feature of the device is the oscillating system and Fig 92 shows the essential units of this system The galvanometers have a high degree of sensitivity yet are capable of carrying extremely high momentary overloads owing to their having high inertia and being heavily damped Galvanometer contacts f_1 and f_2 are arranged to co-operate with contact pieces g_1 and g_2 and, are set in a position equally to obstruct G_1 and G_2 from assuming their normal rest positions

It will be seen that, depending upon whether R_2 is energized or not, either r_{32} or r_{22} will be closed but both cannot be closed simultaneously When r_{22} is closed the full potential of B_1 B_2 exists at f_1 g_1 if they happen to be separated. In the same way when r_{32} is closed, the potential of B_2, B_1 exists at g_2, f_2, if they are apart. The energizing current for R_1 must pass through g_1 f_1 and the energizing current for R_2 must pass through g_2, f_2. Part of the relay energizing current passing through the galvanometer contacts goes through one galvanometer coil and part goes through the other Part also goes by way of T_1 T_2 through the circuit whose e m f is being measured Current through the galvanometer coils tends to rotate both in the same direction the active moving contact being brought more firmly into engagement with its corresponding fixed contact and the inactive one being displaced from its fixed contact.

With the arrangement as shown in Fig 92 with T_1 T_2 open the system will function as an oscillator and its action under these conditions is as follows If the battery connexion at B_2 be removed, both galvanometer pointers will come to rest against their respective fixed contacts They are both shown displaced an equal amount (0 25 mV) above their normal rest position at zero With the connexion restored at B_2, a circuit is completed through R_2, r_{32}, f_2, g_2, coils G_2 and G_1 in parallel to B_2. The passage of current through G_2 secures

positive contact of g_2, f_2 and that through G_1 deflects g_1 from f_1. The energization of R_2 closes contacts r_2 and so energizes R_3, which in turn opens contacts r_{33} and closes contacts r_{32}. It also closes contacts r_{31} which continue to supply R_3 after r_2 has opened. This happens practically instantaneously, the time, that G_1 and G_2 are energized from B_2, B_3 being less than 0·10 sec. The speed of this action in relation to the inertia and damping of the galvanometers limits the travel of g_1 to a relatively small distance.

The closing of r_{32} makes contacts f_1, g_1 'alive' and the opening of r_{33} makes

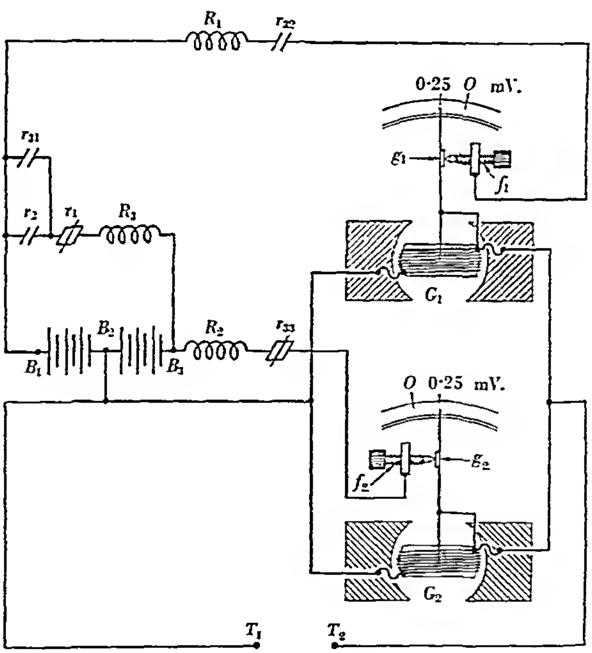


Fig. 92.—Essential units of oscillating system

f_2, g_2 'dead'. g_1 will return from its position of displacement to f_1, the time taken being governed by the extent of the displacement and the damping of the movement. Upon its return to f_1 it will complete a circuit from B_1 through R_1, r_{32}, f_1, g_1, G_1 and G_2 in parallel, to B_2. g_1 will be brought into firm contact with f_1 and g_2 will be displaced from f_2. R_1 will be energized and will open r_1 which will break the circuit to R_3, thus opening contacts r_{31} and r_{32} and closing contacts r_{33}. g_2 will travel from its position of displacement towards f_2 and,

Under the conditions as shown that is with the stationary contacts equally obstructing both galvanometer coils from assuming their normal rest positions, the time each moving contact takes to return will be the same and the time in which R_3 is energized will be equal to the time it is de energized If, however, the moving contacts are not equally obstructed from their normal position of rest, the time taken to return will not be the same for each coil and the period in which R_3 is energized will not be equal to the period it is de-energized A definite relationship will exist between the difference in obstruction and the ratio of time R_3 is 'off' compared to time 'on' With no applied e m f at T_1, T_2, the relationship between the fixed contacts and the normal rest position of the galvanometer coils can be altered only by adjustment of the fixed contacts or the zero position of the galvanometers

Effect of applied e m f When, however an e m f is applied at T_1 T_2 the normal rest position of both galvanometers will depend on the value and polarity of the voltage, and in consequence there will be a fixed proportionality of time 'on' to time off of relay R_3 for every voltage value within the limits set by the adjustment of f_1 and f_2

So far the means for varying the proportionality of 'on' to 'off and not the frequency have been considered This is determined by the extent to which both galvanometer coils are obstructed from their zero positions by the fixed contacts If they are not obstructed there obviously will be no oscillation If set only slightly above zero the frequency will be very low and will increase as the obstruction is make higher up the scale

Whilst Fig 92 represents the basic circuit of the oscillator, in practice the sensitivity of the device is increased and the extent of the instantaneous galvanometer displacement limited by the use of resistances in series with each galvanometer, these resistances being alternatively short circuited as R_3 is energized and de-energized

The relay action which makes one galvanometer or the other dominant at a given instant, also ensures that the 'active' galvanometer has a low resistance in its circuit and that the 'resting' galvanometer is in series with a relatively high resistance These resistances are shown as r_x and r_0 in Fig 93, which shows the oscillating system connected to a potentiometer bridge and thermo couple, controlling furnace F by means of heater H R_3 is used to energize R_1 through contacts r_{31} R_4 controls normally open heater contacts r_{43} in series with the heating element, normally open contacts r_{41} across resistance r_x and normally closed contacts r_{42} across resistance r_0

Positive action at closure of the contacts is assured by the heavy momentary current through the coil As this current is broken elsewhere in the circuit,

The Pyromaster[3] of the Bristol's Instrument Co. is a potentiometer pyrometer with no moving parts in the balancing mechanism except when a change in temperature takes place.

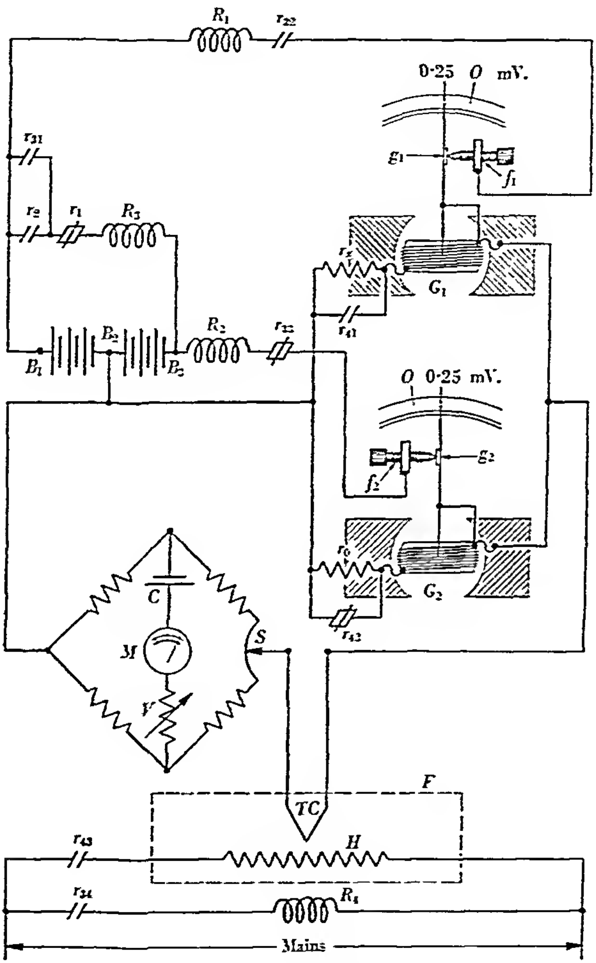


Fig. 93.—Circuit of two position proportional controller

The instrument can be coupled to a pneumatic control system and can act as a proportional control with or without re-set devices.

The basic arrangement is that the e.m.f. of the thermocouple is automatically balanced by suitably changing the position of a slide-wire contact by means of a

reversible motor The slide wire is part of a bridge circuit and the galvanometer has contact pieces very closely on each side of the needle which can deflect about one thousandth of an inch Out of balance of the circuit causes the needle to touch one of these contacts and the circuit is such that an additional current is caused to flow through the galvanometer circuit to force the needle against the contact piece sufficiently to allow enough current to flow to actuate a relay This relay opens one of the two motor circuits allowing the motor to run in a particular direction the motor remaining stationery when both its power circuits are closed Simultaneously when the relay is actuated a second relay circuit is broken which causes the first relay to be de energized and close the motor circuit to stop it Each time the first relay is energized the motor circuit is opened and a movement of the slide wire contact is made This alternate energizing and de energizing continues until the slide wire contact reaches the position of balance and the galvanometer pointer is midway between the two contact pieces and the mechanism is dormant

The Pyromaster can form part of a controller of the pneumatic or the electrical type

Pneumatic type of controller With the pneumatic type the pen arm is attached to a shaped vane moving between opposing nozzles of the type of instrument shown in Fig 44 (Bristol free vane) This system permits the combination of the potentiometric measuring principle with pneumatic control so as to take advantage of the flexibility with the benefits of proportional and floating control

Electrical type of controller The Pyromaster may be used in connexion with electrically operated control apparatus Operation is accomplished through an external relay operating in conjunction with the internal balancing relays

The principle of operation is shown in Fig 94

The Pyromaster recording pen arm mechanism which is linked to the actuating controller contacts having a common contact C with a low contact L and a high contact H in circuit with the external power relay coils M and N and relay contacts in circuit with the Pyromaster internal relay contacts D and E The internal relay circuit F and G are each provided with an additional pair of contacts D and E

In the low off controller the high contact H and the power relay circuit N shown in dotted lines are not utilized On a fall in temperature the recording pen arm through relay F in balancing the potentiometer circuit is moved downwards The common control arm C is moved by the connecting link towards the low contact Similarly on a rise in temperature the Pyromaster relay G moves the contact arm C away from the low contact arm L On each movement of the pen arm by the Pyromaster relays F or G the contacts D or E close The intermittent operation of these relays being such that contact C is moved in a series of small steps towards or away from contact L

Current is supplied to the contact arms C and L only when the pen arm is

moving and the potentiometer circuit is out of balance, and, no matter how close together *C* or *L* may be, no current flows through them when the bridge circuit is in balance and the relay coils *F* and *G* are dormant with contacts *D* and *E* open. Thus the possibility of arcing at contacts *C* and *L* is eliminated. When the common contact *C* closes with the low contact *L*, on an operation of the relay *F*, a circuit is established through the power relay coil *M* which is energized, closing contacts *K* and *J* and shunting contacts *D* on the relay *F*. Relay coil *M* will remain energized as long as contacts *C* and *L* are closed and will hold in, through the lower contacts, the furnace or other contactor gear under control. Immediately contacts *L* and *C* break on a rise in temperature, the relay coil *M* becomes de-energized and the interlock contacts *K* and *J* open, breaking the power circuit which is being controlled.

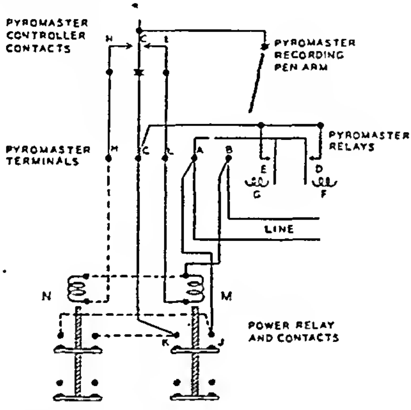


Fig. 94.—Typical Pyromaster Unitact relay

The above explanation refers to a circuit using a relay *M* to give " Low-Off " control. Similar operation can be obtained with relay *N* to give " Low-Off-High " control.

Electronic control

Two electronic methods may be cited as examples of the use of this system in conjunction with potentiometers.

In the one case the unbalanced thermocouple current is converted to alternating current and amplified sufficiently to operate a reversible motor in one direction or the other to move a slide wire until the thermocouple e.m.f. is balanced again (Fig. 95). This balancing motor is geared to the slider on a slide wire, moving it until the voltage *V* is exactly equal to the thermocouple voltage.

The converter is a metal reed, which is made to move up and down 50 times per second, being driven by a 50-cycle coil *E*. Suppose this reed is held upward so that it closes the circuit to contact 1 Now if the thermocouple produces a greater voltage (than battery *B* produces at *V*), this thermocouple voltage forces electrons to flow from 5 through 1*R* and slider 4, to contact 1, down through the upper half of *T* to mid-point 3, back to the thermocouple However, if the slider 4 is moved to the right until voltage *V* becomes exactly equal to the thermocouple voltage, (notice that these two voltages oppose each other,) so that no voltage remains in the converter circuit, no current flows in *T* If slider 4 is moved still farther to the right, voltage *V* now forces electrons to flow up through the thermocouple to mid-point 3, up through *T* to contact 1, back to 4 The electrons flow from 4 up into contact 1 when *V* is less than the thermocouple voltage

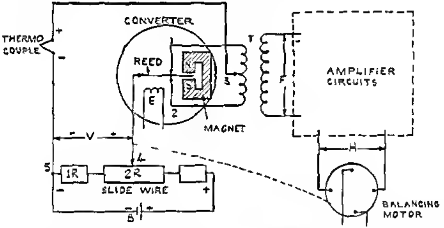


Fig 95 —Thermocouple voltage converter, amplifier, and control motor

The metal reed of the converter touches upper contact 1 during each positive half cycle of the a c power supply To understand why the reed moves upward, note that the permanent magnet has a North upper pole, during the up half cycle, current flows in coil *E* in that direction which magnetizes the reed so that its right-hand end is a South pole, which is therefore attracted upward A half cycle later, current has reversed in coil *E*, and now produces a North pole at the right-hand end of the reed, the reed is pulled down by the South or lower pole of the permanent magnet

When the reed touches lower contact 2, the electrons (which had been flowing up into contact 1) flow now into contact 2, upward through transformer *T* to midtap 3 Notice that as long as *V* is less than the thermocouple voltage the electrons flow through *T* always toward the midtap and alternately through the upper and lower halves of the primary winding of *T*

Meanwhile the secondary of T produces an arc voltage wave which is fed to the amplifier. This makes the motor run, and moves the slider 4 (towards right), this increases voltage V until it equals thermocouple voltage V. When these voltages balance no voltage remains at T, so there is no voltage at H to turn the motor. Although the reed still vibrates there is no motor movement while V is in balance with thermocouple voltage

When slider is, say, too far to the right, so that V is greater than thermocouple voltage electrons flow away from midtap 3 through transformer T out of contacts 1 and 2 toward slide wire.

The electric motor can be of the two winding induction type, one winding is connected to the A.C. supply and the other to the amplifier circuit. (The position of the slide wire is used to actuate the temperature controls electronically.)

As amplification gain is quite high in these instruments, the entire system must be shielded to prevent stray pick-up in the couple circuit; for example the thermocouple circuit can act as an antenna to pick up radiation from the neighbourhood of power circuits, especially when the input-circuit resistance is high. Most of the pick-up can be eliminated by shunting the input circuit with a few hundred-microfarad condensers at the instrument. Another type of error can develop if the thermocouple is earthed at the furnace and the instrument itself is earthed say at the panel. It is well known that there can be quite substantial differences in the potential of two points of earth, and the current that flows from the thermocouple to the instrument as a result of this potential difference may be converted and transmitted through the amplifier to cause serious errors of recording if precautions are not observed. Since furnace gases are conducting at high temperatures it is not always easy to isolate the thermocouple from the furnace electrically.

The other method of using electronic control is with the aid of a photoelectric cell.

Reference has already been made (page 116) to the use of the photoelectric cell in conjunction with the movement of a galvanometer in the Geophysical laboratory type of instrument. Industrial instruments using this principle are now available. Whilst in theory the problem of balancing a potentiometer or Wheatstone bridge with the aid of a photoelectric system is simple, in practice the problem of doing so, without a tendency to hunt and with speed and precision, is complex.[4]

In the usual way a galvanometer detects the condition of balance of a Wheatstone bridge or potentiometer. A beam of reflected light from the galvanometer mirror passes the " controlling edge " of a screen in front of a photoelectric tube. The amplified photoelectric current (see Chap. 15) operates relays which control a reversible motor. As before the motor drives the slide wire contact of the bridge or potentiometer in the correct direction to re-establish balance.

The exact value of the photoelectric current is not important, the photoelectric tube merely acting as a control element to energize relays

Hunting or oscillation is minimized by introducing a time lag in the amplifier input

By reciprocating the "controlling edge" between the galvanometer mirror and the photoelectric tube, throttling control of the heating may be obtained

References

(1) Stockdale *J Sci Instr* 1924 **5**, 392
(2) Abbott *ibid* 1947 **24**, (7) 179
(3) *J Inst of Fuel* 1938
(4) Fairchild and Parsegian *Rev Sci Instr* 1938 **9**, 422

CHAPTER 15

Temperature-control using radiant energy

The total energy radiated from an incandescent solid varies as the fourth power of the absolute temperature. If only the radiation which falls within the visible spectrum is considered, however, it is found to vary approximately as the fifteenth power of the temperature (for temperatures in the neighbourhood of 1500° C) From the point of view of sensitivity, therefore, radiation of energy is a very satisfactory criterion of temperature, since a slight change in temperature produces a relatively large change in energy radiated. It will be readily appreciated that this form of energy should provide a very useful and comparatively accurate means of control at temperatures above 600° C

Total-radiation pyrometers of the type which develop an electromotive force on exposure to the radiations from a heated body can be used with many of the types of regulators described in other chapters. In fact, they may be used with most forms of regulator with which a thermocouple pyrometer may be used, providing the temperature exceeds 600° C Attention will not, therefore, be devoted here to this type, but consideration will be given to another form of radiation-sensitive element.

Photoelectric control in conjunction with electronic devices

A phototube may be used as the sensitive element to respond to changes in light radiations as a result of temperature changes in the sighted object

The phototube consists of a two-element tube having a cathode and anode but no filament or heated cathode. The cathode is usually a half cylinder of metal whose inner surface, when receiving light, is able to emit electrons The energy of light rays striking a surface consisting of potassium or caesium oxide deposited on copper or silver, releases electrons from the metal An increase in light reaching the inner surface causes an increase in the flow of current or electrons through the tube The current flows only when the anode is more positive than the cathode

The current change in the tube is so small when temperature changes are small that its effect is lost unless the entire electrical circuit responding to this charge is kept at steady voltages throughout For convenience most electronic equipments operate from the alternating-current supply. Within these equipments, most of the tube circuits use direct current to give best results. Therefore the first part of the circuit is a rectifier The resulting d c supply

must be carefully protected from changes caused by disturbances other than from the phototube So that while the basic circuit is simple, many parts are added to "brace" the circuit against unwanted signals

Basic Circuit A simplified circuit is shown in Fig 96

A rectifying circuit within the dotted rectangle at the left of the figure supplies a steady voltage between points 4 and 2 The phototube $P4$ and resistor $7R$ are connected across this steady voltage and act as a voltage divider, a middle connection 8 is at the control grid of the valve 3 When the phototube $P4$ is sighted on a cool object, so little current flows through the phototube and $7R$ that the potential at the grid 8 is nearly as low as point 2, by adjustment of the slider $4R$, the cathode potential of the valve 3 is made much higher than the grid 8, so that the valve 3 passes no current Therefore, no current flows through the milliammeter MA or resistor $6R$ With no voltage drop across $6R$, point 7 is at the high (positive) potential of point 4 By moving the slider of $2R$ downward, the grid of thyratron 5 is made more negative than point 7 (cathode) until valve 5 does not "fire" or pass current, relay CR is not picked up, or energized

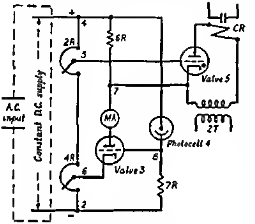


Fig 96—Simplified pyrometer circuit

It may be explained here that a thyratron is a vapour filled valve controlled by a grid When the grid potential rises to some critical value the thyratron passes current, with a snap action, to the full value its external load circuit will permit

When the temperature of the object sighted on rises, the radiation to phototube 4 causes it to pass more current, which must also flow through $7R$, then grid potential at 8 rises and turns on or increases the current flow of valve 3 The current flows from negative point 2, through $4R$ to point 6, from cathode to anode of valve 3, and through MA and $6R$ to positive point 4 This current causes a voltage drop across $6R$, so that the potential at point 7 decreases, lowering the cathode voltage of thyratron 5 until its grid (held constant at point 5 on $2R$) is able to "fire" the thyratron The anode voltage of valve 5 is supplied by a transformer $2T$, so that valve 5 operates on alternating current, although its grid voltage is obtained from the d c system (between points 5 and 7)

The reason for using a c anode voltage is that with d c voltage once the

thyratron is fired it cannot be reset or turned off without opening the anode circuit. With a.c. voltage, during a half cycle, the negative anode voltage is more negative than the cathode so that the current is momentarily stopped as effectively as if the anode were disconnected. Therefore when operating on a 50-cycle a.c. power supply the grid is given 50 chances each second to permit or prevent current flowing in the thyratron. If the anode voltage returns before the gas is de-ionized the thyratron immediately fires.

To return to a consideration of the basic circuit, the anode current through thyratron 5 increases suddenly, picking up relay *CR* when the voltage between cathode 7 and grid 5 has decreased to just the right amount to " fire " valve 5.

To calibrate and operate the apparatus, an optical or other suitable pyrometer is used to show the actual temperature of the hot object. 2*R* and 4*R* are then set so that the thyratron 5 does not fire when the object is at the correct temperature. The milliammeter *MA* may be marked to show the temperatures corresponding to different amounts of current through the valve 3 and helps in adjusting 4*R*.

When the object gets too hot, the increased light radiation reaching phototube 4 causes the thyratron 5 to fire, picking up *CR* to close the relay circuit to give the alarm or adjust the control circuit

Complete pyrometer circuit

Fig. 97 shows how the various units are connected together.

The left-hand side shows that the d.c. supply is provided by a rectifying valve 1 and its filter of the pi type. This filter circuit removes the a.c. ripple or " hum " by making the valve current pass through a reactor *X* consisting of wire wound on an iron core, so that it has a large amount of inductance. This inductance tries to maintain a steady current through its winding by storing energy during moments when the current increases and then discharging this energy to help a decreasing current. A resistor may be used instead of *X*. Similarly, capacitors 2*C* and 3*C* help to smooth the voltage across the load by charging or storing energy during high voltage parts of a wave and then discharging this energy into *X* or into the load, during low-voltage periods.

The resulting d.c. voltage, between points 3 and 2, may still be disturbed by changes in the a.c. supply voltage, so a voltage-regulator valve 2 and its buffer resistor 1*R* is added to produce a more constant voltage between points 4 and 2.

By the addition of 3*R* and 5*R* in the voltage divider the voltages at sliders 5 and 6 are held within desirable limits, so that 2*R* and 4*R* provide easy adjustment.

Valve 3 is a pentode whose screen is connected to a positive point 4 and its suppressor is connected to its own cathode. This type of valve gives an

output of current through $6R$ that is not affected by changes of anode voltage at point 7.

To prevent any change in a c filament current disturbing the anode current of valve 3 a ballast device holds constant the current in its own circuit In this ballast the current flows in a filament of iron, thus heating it Within its operating range, any increase of load current raises the temperature of part of this filament and increases the resistance of the filament After a short time lag, this increased resistance brings back the current to its previous value Thus the current to the valve filament is kept constant

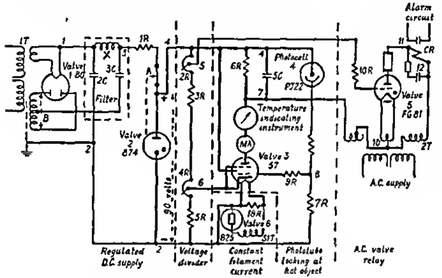


Fig 97.—Circuit of photoelectric pyrometer

Electronics in Industry Chute (McGraw Hill)

Capacitor $5C$ steadies the voltage across $6R$ and prevents thyratron 5 from being fired by any momentary increase in valve 3 current

Near the thyratron 5, resistor $10R$ limits the amount of grid current to it The grid circuit of the thyratron valve contains the secondary winding of a transformer $2T$ between points 7 and 10 and a "ripple" a c voltage helps to fire the thyratron during the first portion of the half cycle of anode voltage, or prevents it from firing at all This is a circuit refinement and is intended to ensure that full voltage is applied to energize the relay thus providing a more positive pick up

CHAPTER 16

Electrical-induction regulators

INDUCTION regulators can be arranged to maintain either a constant current or a constant energy supply to the furnace.

In principle the Induction Regulator is a transformer built on the lines of an induction motor, and having the important characteristic that, although normally stationary whilst working, the relative positions of the secondary and primary windings can be altered by moving the rotor. This gives to the induction regulator characteristics very similar to those of a transformer having a variable ratio of turns, and since the method of adjustment, namely, turning the rotor, is perfectly smooth and continuous, the regulator has a regulation equivalent to that of a transformer having an infinite number of tappings over the working range. The supply is carried to the primary winding, while the secondary windings are connected in series with the circuit of which the voltage is to be regulated. The primary winding may be mounted on either the stator or the rotor, depending on the output and voltage, the secondary being mounted on the opposite part. As the feeder voltage rises or falls beyond set limits, the voltage-regulating relay closes contacts which energize one or other of a pair of contactors. These in turn control the direction of rotation of a motor and cause it to drive the rotor spindle of the regulator through spur and worm gear, which raises or lowers the feeder voltage as may be required. Directly normal voltage is restored, the action of the voltage-regulating relay causes the motor to stop. In some circumstances, induction time-delay relays are used to energize the motor-control contactors after a suitable time-interval, in order to avoid response of the induction regulator gear to variations in the voltage that are merely momentary.

These regulators are suitable for industrial resistance furnaces and for furnaces of the submerged arc type where the electrodes are stationary.

Fixed-Induction Furnaces.—An ingenious stationary or fixed form of automatically regulated induction furnace has been described by Perrin and Sorrel [1] This furnace is suitable for use only where the number of heat-treating temperatures required is limited, as it is necessary to use a separate furnace for each temperature. This is not inconvenient in cases where large quantities of steel articles have to be heat-treated at the same temperature. An advantage of this type of thermostat is that no pyrometer is needed. The principle of the furnace is very simple. A muffle or tube *A* (Fig. 98), made of a metal selected according to the temperature required, is surrounded by a non-magnetic

conducting material *B* The latter is made the secondary of a transformer fed by alternating current from the power mains The current generated in the secondary depends, *inter alia*, on the specific induction of the furnace tube This current heats up the secondary, and therefore the tube until the latter reaches the temperature at which it loses its magnetism, when its specific induction falls, and therefore the coupling between the primary and secondary of the transformer also falls rapidly and the less heat is generated in the secondary So long as the total heat generated in the secondary—when the tube is non magnetic—is insufficient to keep the furnace temperature above the magnetic change point, the tube will not rise above this temperature

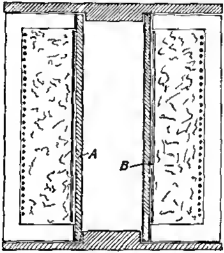


Fig 98 —Induction furnace with automatic temperature-control

It is necessary to make the furnace tube of a material[2] which has a quickly reversible change of magnetic property at the working temperature Materials that have been used are the alloys of cobalt, such as ferro cobalt which when suitably selected can be used for temperatures of from 750° to 1100° C Below 750° C, ferro nickel and ferro nickel-cobalt may be used The secondary can be made of nickel for temperatures above 350° C whilst nickel chrome, copper, aluminium or its alloys can be used for other suitable temperatures

Naturally the closeness of control will not be so accurate as with some other forms of regulators but the absence of auxiliary mechanism is a great advantage The closeness of control will be governed to some extent by the efficiency of thermal insulation, and the size of the furnace

References

(1) PERRIN AND SORREL *Rev de Met* 1931 No 8 448
(2) JACKSON AND RUSSELL *Instruments* 1938 11

CHAPTER 17

Low-temperature control

CRYOSTATS

THE apparatus used to maintain constant temperatures below 0° C are termed "cryostats," and can be divided into five general classes, some of which are automatic in action. They are as follows—

(1) Those employing boiling liquids. This type was largely developed by Onnes at Leiden. Control to $\pm$ 0·01° for periods of an hour or so can be effected by regulation of the pressure on a liquefied gas. Any of the following gases are suitable: methyl chloride, nitrous oxide, ethylene, methane, oxygen, nitrogen, hydrogen and helium. This method is somewhat expensive.

(2) Those involving addition of liquid air to the cryostat bath by hand.

(3) Those in which the flow of heat into a large metal block is regulated, the lower end of the block being intermittently dipped into liquid air. This method is satisfactory if care is taken to place the thermometer and experimental apparatus at identical heat-gradients.

(4) Those in which the flow of heat into the cryostat is regulated by means of a partially-evacuated Dewar flask, which is inside a larger surrounding Dewar flask containing liquid air. This type of cryostat may be made automatic.

(5) The automatic cryostat proper.

In this chapter, consideration will be devoted to the automatic type only.

Principles of low-temperature control

Automatic low-temperature control involves the use of a means of producing low temperature, a suitable liquid as a bath fluid, and a thermostat. The thermostats employed here are the same in principle as those in use for temperatures above zero, and have been described in earlier chapters. No detailed description is therefore necessary, except where a special feature is involved. Brief reference only will be made to the means of producing low temperatures and the bath liquids used, as these do not properly come within the scope of this book. References, however, will be found at the end of the chapter to some of the more important published works on the subject. The list is not intended to be exhaustive.

A simple method of low-temperature control is to immerse the objects to be treated in a cooled bath of some liquid whose physical properties, such as fluidity, boiling-point and freezing-point, are suited to the working temperature. Regulation can then be effected in one of two ways: either (1) by controlling

the flow of the refrigerant, or (2) by setting the flow of the refrigerant for a slight excess cooling, and arranging a thermo regulator of some form to control electrical heating in order to compensate automatically for this excess cooling The latter method is particularly suitable on account of the ease of control of electrical heating

Baths

Fairly complete lists of bath liquids suitable for use in the low temperature range are given in the publications of the Leiden Cryogenic Laboratory, and in the Bureau of Standards paper 520, but the following liquids may be cited as being in common use —

	Temperature range (° C)
Brines	− 40 to −170
Paraffin oil	− 40 — 75
Petroleum ether	−130 — 40
Acetone	− 94 — 56
Ethyl alcohol	−114 — 78
Toluol	− 95 −110
Isopentane	−160 — 28
Propane	190 — 45
Propylene	−190 — 48

An objection to the use of brine is its corrosive action on metal containers Ethyl alcohol becomes very viscous before it freezes Propane has to be kept at a temperature below −40° C, or stored under pressure

Cooling

The expansion through valves and cooling coils of ammonia, carbon dioxide or other suitable substances, may be used to cool the liquid Solid carbon dioxide may also be used as a cooling medium A carbon dioxide slush bath, consisting of solid carbon dioxide with a suitable liquid such as petrol, alcohol or ether, affords a means of attaining temperatures down to about −78 5° C at atmospheric pressure

For temperatures as low as −180° C, compressed air may be used as a refrigerant Liquid air may be utilized by employing either the liquid or superheated or saturated vapour as a bath, or again by using the vapour or liquid to provide cooling for a thermostat bath The liquid air should be aged, that is, allowed to remain in the container for about 2 days since the freshly made liquid tends to give unexpected fluctuations in the temperature of the bath Due to progressive concentration of oxygen in liquid air residues, extreme care should be taken to prevent the mixing of these residues with any inflammable substance Electric motors should be so placed as not to provide a source of ignition for inflammable vapours If liquid air is used for cooling the bath liquid can previously be well cooled with a freezing mixture of ice and salt in order to save consumption of the liquid air

A somewhat unusual method of cooling has been used by Lundstrom and Whittaker.[1] Attached to the wall of the bath, which is made of copper, is a copper rod which is immersed in liquid ammonia or ice, depending on the temperature required. The bath is then cooled by the conduction of heat away by the copper rod. A cooling coil in the bath is therefore unnecessary in this case.

Insulation of the bath

As the production of cold is generally a somewhat difficult and expensive process, the insulation of the bath from undesirable access of heat is especially important.

The tendency for atmospheric moisture to condense on the bath and its accessories must also be guarded against by suitable insulation.

In the choice of insulators, consideration has to be given to suitability for the temperature, and some materials are very absorbent of condensed moisture and should therefore be avoided. Cork, either in the form of slabs, fine granules or shavings, or hair felt may be recommended. Cork-shavings, a waste product from cigarette-tip manufacture, weigh on the average 3 lb. per cubic foot. Cork has a thermal conductivity of the order of 0·00008 gramme-calorie per square centimetre per second for a temperature-difference of 1° C per centimetre thickness.

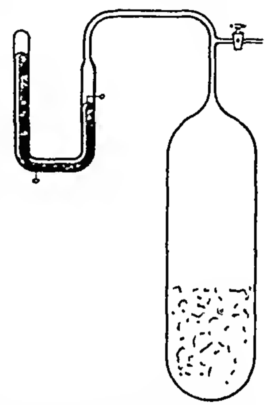


Fig. 99.—A control device for low-temperature work

Thermostats for low-temperature work

The usual electrical type of toluene and mercury instrument (described in Chapter 3) or a bimetallic-strip form (Chapter 11) can be adapted for this type of work.

A simple device for observing and controlling low-temperature baths, in which use is made of the absorption properties of charcoal at low temperatures, is shown in Fig. 99. A tube, partially filled with granular charcoal and a gas, is connected to a manometer (a simple U-tube with mercury). The level of the mercury surface will depend upon the amount of the gas held by the charcoal, that is, upon the temperature of the charcoal. Electrodes are sealed in and control the heating circuit through the medium of relays in the usual way. The range of greatest sensitivity is obtained by the selection of a suitable gas in contact with the charcoal, and argon is such a gas. The pressure of the argon may be about 20 centimetres when the charcoal is at room temperature. The space above the mercury in the other limb of the manometer is evacuated.

Forms of automatic cryostats

In the Hearson apparatus for temperatures between $-10°$ and $+20°$ C, the withdrawal of heat is brought about by the evaporation of liquid sulphur dioxide which, after use, is re-compressed and again rendered liquid by means of a small refrigerating plant The maintenance of any particular temperature depends entirely upon the rate at which evaporation and re-compression of the gas takes place these rates being dependent upon the rate at which the compressing motor works For the regulation of the speed of the motor a bimetallic thermostat is used

A cryostat employing pentane cooled by liquid air and capable of maintaining any temperature between $-180°$ C and $0°$ C has been described by Keyes, Townshend and Young[2] The pentane is contained in an unsilvered Dewar vessel, the vacuum space of which can be exhausted through a side tube This vessel is immersed in a larger silvered one containing liquid air The pentane is cooled by the heat flowing across the vacuum space of the inner vessel to a greater or less extent as the vacuum is low or high The pentane is kept well stirred and cooling is balanced by supplying heat electrically from a heating-coil in the pentane The temperature is maintained and controlled by means of a twisted bimetallic strip By adjusting the pressure in the vacuum space of the inner vessel and also the heating current any particular temperature between -180 C and $0°$ C can be obtained This cryostat is said to be capable of automatically maintaining the temperature constant to about $0\ 1°$ C Finer regulation of the temperature has been achieved by L C Jackson[3] by employing the triode-valve relay method.

A cryostat described by Egerton and Ubbelonde[4] (see Fig 100) keeps the temperature constant to $\pm 0{\cdot}1°$ C down to about -160 C and does not consume much liquid air The principle employed is the same as that of the foregoing apparatus of Keyes, Townshend and Young in that regulation is effected by control of the flow of heat between a metal vessel *D*, filled to a constant height with liquid air, and the bath liquid by altering the pressure of gas in the jacket separating the two The method of control, however, is different The lagged Dewar vessel *A* contains the bath liquid A blower forces liquid air from the Dewar flask *C* through a siphon into *D* and thereby cooling the bath liquid in *A* Since there is no danger of the vessel *D* breaking and mixing liquid air with the bath liquid it is quite safe to use petrol freed from water as a bath liquid The method of operation is to bring the level of liquid air in the double-walled copper vessel *D* to the correct height, the dimensions of *D* having been carefully chosen for proper functioning by taking into account the amount of heat to be conducted across the heat space and down the walls The space between the walls is brought to a low vacuum, and the pressure is made such that with the level of the liquid air at a certain height the bath reaches equilibrium at a temperature slightly below the desired

temperature. The level is maintained by control of the blower forcing the liquid air over into D, this being done automatically as follows. A fine glass tube with splayed-out end is connected to a tambour, on the rubber diaphragm of which rests a lever which makes and breaks the electrical circuit of the blower. The pressure in the tube and tambour is dependent on the covering and uncovering of the end of the tube with liquid air. Provided the rate of stirring is suitably adjusted, the maintenance of a constant level of liquid air in D is alone sufficient to keep the bath temperature within 0·5° C, in spite of the change in composition of the liquid air with time. It is necessary only to control the

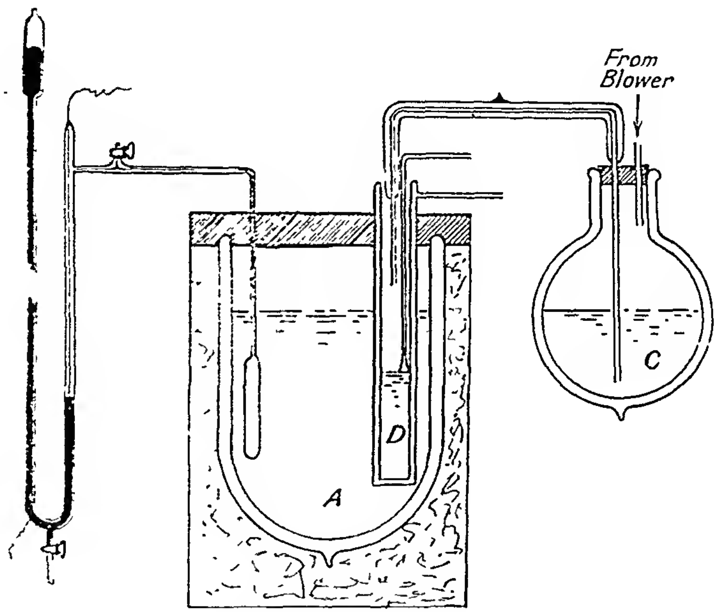


Fig. 100.—Egerton and Ubbelonde cyrostat

pressure in the air space in D in order to obtain automatically a much finer adjustment of temperature. For this purpose the air space in D is connected to a water-pump when the bath temperature is a little too high, and to a high-vacuum pump when the bath has been cooled a little below the desired temperature. The normal connection is with the low vacuum, but when a gas thermometer in the form of a thermostat closes a contact, a relay brings the high vacuum into action.

An automatic cryostat that incorporates a number of interesting features is that described by Sinozaki and Hara[5] (Fig. 101). The bath liquid, consisting of petroleum ether contained in the Dewar vessel A, is cooled by liquid air

from the vessel K by means of a cooling coil of copper piping D. Absorption of heat by the vessel K causes evaporation of the liquid air and an increase of pressure. This causes the liquid air either to pass over into the cooling coil or to escape against the water head h. The valve P is controlled through the solenoid S, by a thermostat G. This consists of a copper vessel filled with liquid pentane and containing a bundle of thin copper strips to improve heat conduction. The expansion of the pentane moves a column of mercury in a U tube to make and break an electrical circuit, consisting of an accumulator

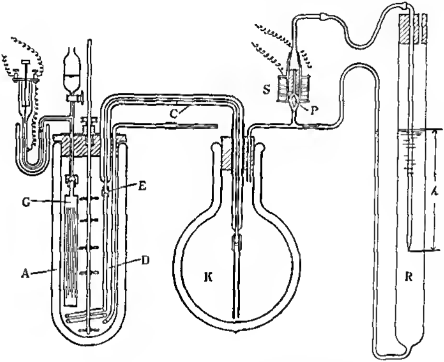


Fig 101.—Sinozaki and Hara automatic cryostat

in series with the solenoid S. If the temperature rises the valve P closes and when the temperature falls, the plunger drops by gravity and the valve is opened. This closing and opening of the plunger-valve increases and reduces respectively, the pressure in the liquid air reservoir K and consequently increases or retards the flow of liquid air through the vacuum jacketed tube C into the cryostat bath. The liquid air enters the cooling coil through a jet E in the form of drops, and the amount is such that its cooling effect nearly compensates for, but never exceeds the heat flow from outside into the cryostat bath. If the gas pressure in the liquid air reservoir is accidentally increased too much for

example by a stoppage of the jet E, the glass tube leading from the reservoir K, to the bottom of the water tank R serves as a safety-valve. The temperature of the bath may be maintained constant automatically from $\pm$ 0·02 per cent to $\pm$ 0·003 per cent within the range 0° C to $-$ 150° C for several hours if the apparatus is suitably adjusted. About 3 litres of liquid air are consumed in order to cool down a cryostat of 1,400 c.c. capacity from zero to $-$ 100° C and maintain it at this temperature for nearly 30 hours. Pentane becomes viscid at a low temperature, and is not suitable as a regulator liquid below $-$ 150° C. If butane be used for this purpose and for the bath liquid, this cryostat can be used at as low a temperature as $-$ 180° C.

In a cryostat devised by Roper[33, 34] for temperatures from $-$ 35 to + 25° C a commercial household type of refrigerating machine is kept in constant operation ; an expansion valve in the liquid refrigerant line allows various quantities (depending on the manual setting of the valve orifice control) of expanded cold liquid phase to enter the evaporator coil immersed in the liquid bath. With proper adjustment of the expansion and constant pressure valves, an equilibrium temperature is soon reached in the bath. This temperature is below the required temperature and a continuous electrical energy is then admitted to the bath until a temperature a few degrees above the cooling-equilibrium temperature is reached, this continuous energy input is then reduced in magnitude until it does not quite balance the energy withdrawn by the refrigeration system. The on-off intermittent energy input is then placed in operation, along with a modulator. The latter serves to vary the continuous energy input slowly, the amount of variation being a function of the length of time that the intermittent heater is on and is off ; such a type of modulation tends to counteract the effect of any slow, external changes upon the system.

The evaporator coil is run almost dry, that is only a small amount of evaporating liquid refrigerant spray may be present at any one time. In this manner the coil is kept at a given temperature irrespective of the bath temperature, in contradistinction to the wet method of operation in which the evaporator is kept filled with liquid phase ; under such circumstances the refrigeration system will attempt to keep the bath (and the coil) at a constant temperature.

To change the bath from one operating temperature to another, excess refrigeration or excess electrical energy input is employed to attain approximately the desired temperature ; since it is considerably easier to perform minute changes by means of the electrical energy input than by means of the refrigerating effect, the final adjustment is made by the former means.

It was found that if the on-off energy input to the bath were supplied by a separate heating coil from the steady heater that frosting of the inside of the former took place, owing to the "breathing" effect, to the minute amount of energy being dissipated and to the fact that the coil was only energized approximately half of the time. By superimposing the intermittent energy

input upon the steady current on the one heating coil these difficulties were overcome and also the thermal lag in the intermittent heating was slightly decreased Modulation of the continuous energy input to the bath was found necessary since external variables such as room temperature, barometric pressure, and electrical supply line voltage influenced the operation to an appreciable extent

To obtain reproducibility in the thermostat itself it is necessary to seal it hermetically after evacuating to say 0 2 mm

Ruh[40] and his collaborators used a three bath system to obtain temperatures ranging from 40° to − 70° F for viscosity determinations

The first bath consisted of a jar held at a suitable low temperature, containing solid carbon dioxide and isopropyl alcohol, a second bath was a jar under rough thermostatic control, and a third, a Dewar type jar under close control Acetone was chilled by circulation through a pipe in the first bath and passed to the second bath which was controlled by a bimetallic thermoregulator and an electric immersion heater Immersed in this second bath was a coil to supply cooled acetone to the third Dewar jar, in which were immersed a bimetallic thermoregulator and an immersion heater

Replacement of bath liquids

Apart from replenishment to make up for evaporation losses it is necessary to replace the liquids in low temperature baths from time to time, as their usefulness is impaired by the absorption of moisture This is most rapid when atmospheric humidity is high

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CHAPTER 18

Relays and valves

THERMOSTATS sometimes operate the cut-off switches or valves directly, but in most cases through the medium of relays. A number of these regulating devices have been described in connexion with the particular thermostats In the laboratory the most valuable forms of relay are the thermionic valve and the hot-cathode, grid-controlled, gas-filled types, to which numerous references have been made in the text and at the end of this chapter The drawback of complexity is counterbalanced by the high sensitivity that can be attained by their use The following are cited as further examples of relays, but the list is not exhaustive

Galvanometer relays

Galvanometer movements can be adapted to become sensitive relays for the control of other circuits providing the galvanometer is carefully protected from vibration (see page 114) The stability of a galvanometer is greater, and it is much more positive in its action, than an electronic valve for small voltage changes, as without any elaboration of the circuit it will operate at exactly the same value indefinitely Again, it is not dependent upon anode voltage or filament current for its sensitivity. It is obvious that the size of the contacts which can be operated by the galvanometer movement is very small, and the current which can be broken must be minute, as any arcing would seal the contacts together For this reason it is often preferable to control the grid potential for a valve or "thyratron" by the galvanometer relay, and to use the valve to control larger currents The contacts can be made of fine platinum wire A wire tongue attached to the moving coil can be arranged to make contact with a fixed wire when the coil is deflected By using fine wires, sticking of the contacts is minimized, as only a very small surface is in contact By suitably positioning the wires a rubbing action can be produced The power required to operate a sensitive galvanometer relay is of the order of 1,000 to 2,000 $\mu\mu W$

Electronic relay

A number of electronic relay circuits have already been referred to in this book and a large number have been described in the literature, reference to some of which is made at the end of this chapter

With the aid of these relays the regulator contact current can be of the order of a few microamperes only.

In using these relays, it is necessary for the regulator elements to be well insulated and the connecting leads kept as short as possible and well insulated, since any reduction in the necessarily high open circuit resistance, due to high humidity or insulation leakage, may prevent the normal working of these relays.

A versatile relay of the electronic type has been described by Baier and Millington[1], in which, by means of a six-point selector switch with a potentiometer, the relay can be adjusted for use with any type of regulator having contact and connecting wire lead resistances from approximately 0 ohm to 250 megohms.

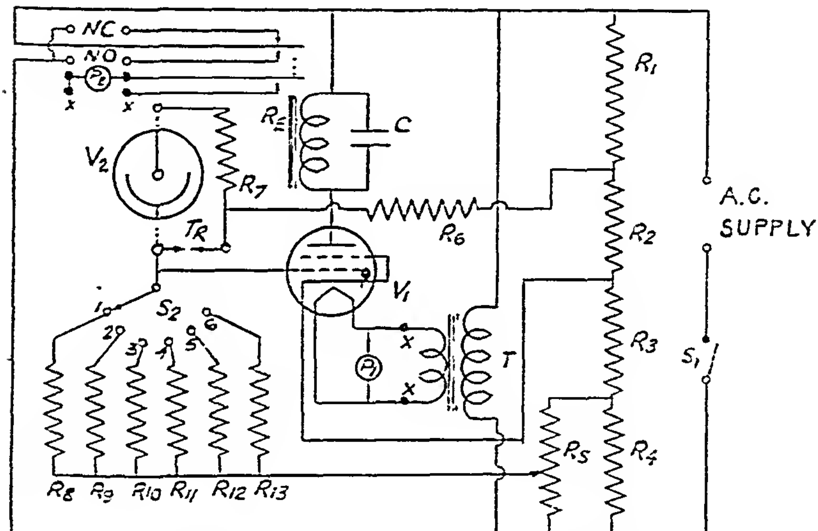


Fig. 102.—Circuit diagram of adjustable electronic relay

The relay is also provided with a socket to receive an emission-type photocell for light activation of the relay, to operate either alone or in conjunction with the usual type or regulator.

The relay circuit is shown in Fig. 102. A gas tetrode valve operating on alternate half waves of the alternating current cycle is used in a conventional circuit. This valve should have a high current-carrying capacity and a triggering action of the grid where, when the critical grid firing voltage is reached, the valve conducts to its maximum capacity. The necessary voltages for plate and grid operation are obtained from the voltage divider R_1 to R_4 with the voltage developed across R_1 and R_2 supplying the plate a voltage, positive with respect

to the cathode and the voltage across R_3 and R_4 negative with respect to the cathode on the same half cycle for grid control R_3 gives a minimum negative grid bias voltage just in excess of cut off while R_4 allows for an additional grid bias voltage variable to the grid through the potentiometer R_5 The use of the resistors R_8 to R_{13} allows for the ranges of sensitivity desired for the operation of the relay With S_2 in position 6 and the control on R_5 moved all the way up (minimum setting) the relay will operate with contact resistances across the thermoregulator contacts T_R of as much as 250 megohms while with S_2 in position 1 and the control of R_5 all the way down (maximum setting) practically a zero resistance is necessary

If the circuit is to be turned on and off frequently it is advisable in most cases to insert a switch in the plate circuit to provide a short delay for a few seconds after turning on S before applying the voltage to the plate of the valve V_1 This is recommended since turning on the heater and plate voltages simultaneously may result in shortening the life of the valve A holding condenser C is necessary to prevent chattering of the plate circuit relay R_E since the operation of the relay depends upon half wave plate rectification The plate circuit relay R_E has a set of single pole single throw contacts connected to a pilot lamp to indicate operation and a set of single pole double throw contacts to deliver the alternating current necessary for the operation of the desired control device This dual outlet permits of normally open or normally closed arrangements The transformer T is a filament transformer fo the valve R is a current limiting resistor for photocell if used

R_6 is a regulator contact protective resistance and should be of high value.

Operation of the circuit —With the regulator terminals T_R open or if used the photo electric cell dark (or at some predetermined light intensity depending on the setting of S_2 and R_5) the grid of the valve is at a voltage more negative than the critical grid firing voltage as determined by R_3 and the setting of R_5 When the contact T_R is closed or the photocell illuminated (or the illumination increased) the grid is brought to a potential less negative than the cut off voltage, causing the valve to fire and energize the plate circuit relay After connecting the relay to a thermoregulator with the contacts T_R open switch S_2 can be moved progressively from contact 1 toward contact 6 and if the relay operates owing to leakage across the wire leads from the regulator switch S_2 can be backed off one position (or the setting of R_5 lowered) until the plate circuit relay R_E does not become energized except when contacts T_R are closed

Mercury-in glass switches

Mercury in glass switches are now in general use for technical and industrial purposes Contact is usually established between mercury and mercury and not mercury and metal in order to avoid arcing with heavy currents and high voltages which would cause melting of the electrode and leakage at the sealing

point. The leading-in electrodes are contained in pockets in the glass envelope and are covered with a pool of mercury. To prevent oxidation and to keep the mercury clean, the tubes are filled with a reducing gas. Owing to the small amount of mechanical energy and minimum of movement required to operate such switches, which can break fairly large currents, only a small current is necessary to operate the solenoid. Many forms of switches are available, from the simple form which makes and breaks a circuit (see Fig. 87) to that in which it is possible to make and break two distinct circuits. This latter type is useful where it is required to operate a circuit which controls a cooling medium in addition to the heating circuit.

A switch of the solenoid type is illustrated in Fig. 103, in which the mercury is displaced by the movement of a core actuated by the solenoid.

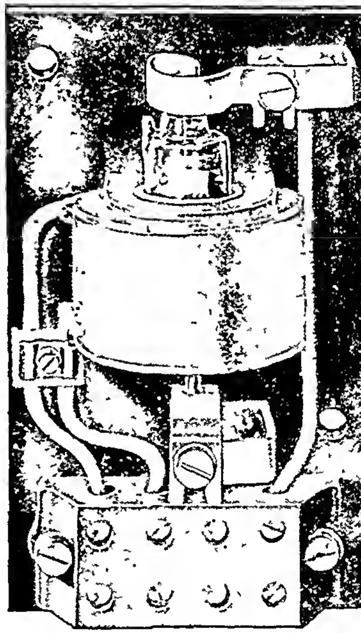


Fig. 103.—I.A.C. mercury-in-glass switch

Hot-wire relays.—A simple method of operating a mercury switch in response to impulses from the thermoregulator is the hot-wire relay of Griffin and Tatlock, Ltd.

The essential feature of the apparatus is a wire supported between a standard and a tensioning screw in another standard. On the passage of a current through the wire, it becomes heated, the expansion causing it to sag. This sagging of the wire is used to effect the tilting of the mercury switch through a link attached to the cradle which supports the switch. One method of setting up the circuit is to connect the thermostat (which may be of any electrical type) in parallel with the wire element. When the thermostat "makes," the wire element is short-circuited, and the current through it being thereby reduced, the wire cools and contracts. The effect of its contraction is to tilt the mercury switch, and thus to break or make the main circuit. By the parallel method of connexion, the electrical power broken at the thermostat contacts is much less than when the thermostat is in series with the wire element.

The Sun-Vic hot-wire relay operates on the same principle, but the wire is enclosed in a vacuum tube together with the contacts, which are of the metal type.

An ingenious vacuum switch manufactured by Siemens and Halske consists of an evacuated glass tube containing two contact springs sealed in at one end and a flexible corrugated tube sealed in at the other end Through the flexible tube projects a rod a slight movement of the outside end of which will cause the inside end to open the contact The movement of the rod by, for example the expansion and contraction of a material can thus be arranged to make or break an electrical circuit The rupturing capacity on a non inductive load it is claimed may be as much as 1 500 volts at 10 amperes

Time-delay relay

A pronounced improvement in operation of thermostats is often obtained by supplying the heat intermittently instead of continuously near the control temperature Heat is supplied in small increments by this method which helps to prevent over regulation of the temperature This is basically the Gouy principle (See page 19)

Chattering or the too frequent operation of a sensitive relay can also be minimized by a time delay device This is particularly applicable to bimetallic types of regulator

A mechanical method of effecting this intermittent action is by using a clock with a sweeping second hand brushing over a metallic strip so that electrical contact is maintained for a short period only

Another method[3] is to use the cathode heating time of a thermionic valve as the basis of the time delay switch Likewise the delay action may be achieved[4, 5] by utilizing the heating time necessary to allow electrons to flow from the cathode to the plate of a vacuum tube rectifier

A basic circuit is shown in Fig 104 Electrons flow up through R_4 to the cathode of the valve Voltage is maintained across the resistance R_4 by the by pass resistor R_5 If the switch S is in the position B electrons will flow through R_3 to charge condenser C_1 Initially S is in the position A and the grid is in effect short circuited to the cathode by R_1 and R Current flows in the valve and causes the relay to close switching S from A to B position Electrons flow through R_3 charging C_1 so that the grid side becomes negative As C_1 charges the plate current of the valve decreases and when it has reached a value too weak to hold the relay closed S is switched from B to A The time delay before the relay opens is controlled by the capacity of C_1 and the value of the resistor R_3

C_1 can now discharge through R_2 and does so at a rate controlled by the condenser capacity and the resistance of R_2 As C_1 discharges the grid potential approaches that of the cathode and the plate current rises At a value of the plate current sufficient to close the relay S is switched from A to B again and the cycle repeats The time of charge and discharge is regulated by the condenser C_1 The ratio of off to on periods can be varied by changing the

ratio of the values of R_3 and R_2. If R_2 is greater than R_3 the time for charging C_1 will be greater than for the discharge, and the relay contacts will be closed for a longer period than they are open.

In order to vary the off-on ratio a number of resistors from say 1 to 20 megohms on a multiple contact switch may be substituted for R_3 see Fig. 105. In order that the period of time for which the contacts are closed can be either greater or less than the time period they are open, a single-pole, double-throw switch is used for R_2 with two resistors of say 1 and 20 megohms. Changing from one resistor to the other in R_2 inverts the open-closed time ratio.

In the complete circuit shown in Fig. 105, S and B are the two halves of

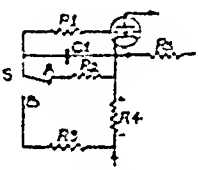


Fig. 104. Simplified time-delay relay circuit

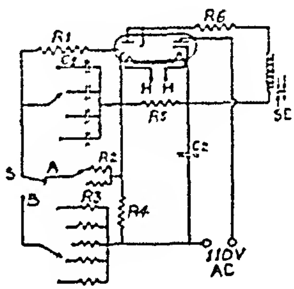


Fig. 105.—Time-delay relay circuit

double-pole, double-throw relay contacts which are simultaneously actuated by the relay coil. The resistor R_6 in the plate circuit reduces the plate current to suit this relay coil.

Valve-operating gear

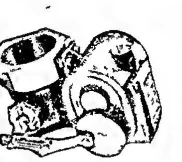
As previously mentioned, the switch may directly control the current to a furnace, or may operate through a motor moving a valve controlling the supply of air, steam, water, oil, etc.

A simple motorized valve gear for a single supply line is illustrated in Fig. 106. Where more than one valve or damper has to be controlled, a mechanism of the form shown in Fig. 107 may be used. The electric motor is coupled to a speed-reduction gear-box by a clutch adjusted to slip when a predetermined resistance is met, thus preventing the motor or gears from being damaged should a valve stick.

Valve-operating gear may take the form of a power cylinder capable of developing from about 360 to 5,500 ft-lb per stroke. Such cylinders are capable of operating large slides or valves. The thermostatic regulator controls a pilot

valve which determines the direction of air, water or oil flow to the power cylinder

It is sometimes found that the arrangement of the pipework supplying the fuel and air to a manually controlled furnace is such that more than one valve-operating gear is necessary if automatic control is adopted This entails unnecessary expense, and the efficiency of control is impaired owing to the difficulty in co-ordinating the settings of the various valves so as to ensure the correct fuel/air ratios By re-designing the layout with the controls in line, it is possible to use one valve operating gear to control two, three, and sometimes four valves, obtaining, at the same time, improved results



g 106 —Cambridge motorized lve gear for single supply pipe

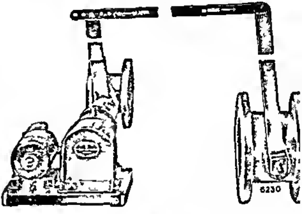


Fig 107 —Cambridge valve operating gear

VALVES

Control valves

The selection of a suitable valve for the requirements of an installation requires careful consideration The material of the valve body and seats will be governed by the normal and maximum temperatures and pressures of the controlled medium Bronze bodies are suitable for use where the temperature does not exceed 500° F and the pressure does not exceed 250 lb The corresponding limits for cast-iron are 500° F and 150 lb , and for cast steel, 750° F and 300 lb Seatings are chosen from such materials as bronze stainless steel, nickeloy, etc The wearing or erosive action is closely related to the pressures employed and the size of the valve If, for instance, a single beat valve is operating in an almost closed position for normal running, and the velocity of the fluid is high, the valve seatings will become " cut " In the case of steam, this causes " wire drawing "

It may be found that a comparatively small valve will give the requisite control when the plant is running but is unsuitable for rapid heating when starting up. By using a larger hand-controlled by-pass valve or a V-ported valve or possibly an on-and-off valve, this difficulty may be surmounted. A large single-beat valve working in an almost closed position will be unreliable, because slight variations of opening will cause large variations of flow.

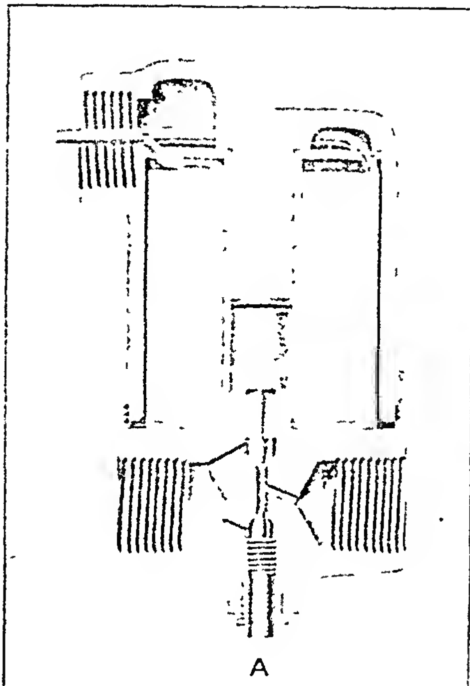


Fig. 108.—" Arco " solenoid valve

Solenoid valves

Solenoid valves are often used when a controlling device operates electrically. Here a globe- or needle-valve or balanced plunger is normally held open (or shut) by means of a spring. Passage of current through the coil of the solenoid causes the armature to move to the other extreme of its travel, so that the valve is then fully closed (or open) (see Fig. 108). The chief advantages of this type are its low cost and simplicity. It is not as reliable, however, as the motor-operated valve, in which a large operating force is available, which gives better control and more freedom from sticking.

Motor-operated valves

In this type as previously indicated a geared down electric motor operates the valve through an eccentric A single seated valve is generally used To prevent over running of the motor and consequent opening of the valve, rotary snap switches break the circuit at each half revolution

Diaphragm valves

These valves have a diaphragm top which is operated by an air supply regulated by a valve in the controller The valve may be of the balanced or unbalanced type and designed for use with air water oil or steam Wherever

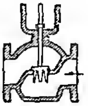


Fig 109 Direct action single seated valve

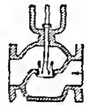


Fig 110 Reverse action single seated valve

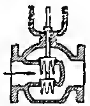


Fig 111 —Direct action, double seated valve

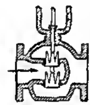


Fig 112 Reverse action double-seated valve

possible it should be of the V port type as this assists in obtaining smooth control

Diaphragm valves are of two types *direct acting* (see Fig 109) and *reverse acting* (see Fig 110)

A direct action control valve closes as the pressure on the diaphragm is increased It opens as the pressure is reduced A reverse action control valve opens as the pressure on the diaphragm is increased It closes as the pressure is reduced When the application is such that the valve must automatically close as a safety measure in case the air pressure to the diaphragm fails a reverse action valve should be used Fig 111 shows direct action double seated normally open Fig 112 reverse action double seated normally closed Fig 109 direct action single seated normally open Fig 110 reverse action single seated normally closed

If the line pressure is not too great, single globe valves are used, but for greater line pressure, balanced valves may be needed. The action may be either throttling or "open and shut." In a throttling valve (double-seated V-port) (Fig. 114) the disc or plunger seeks a position where line-pressure drop plus spring pressure balances control pressure and permits continuous flow of the heating medium. Open-and-shut valves are either fully opened or fully closed at all times. They are usually preferred where the temperature-lag in the

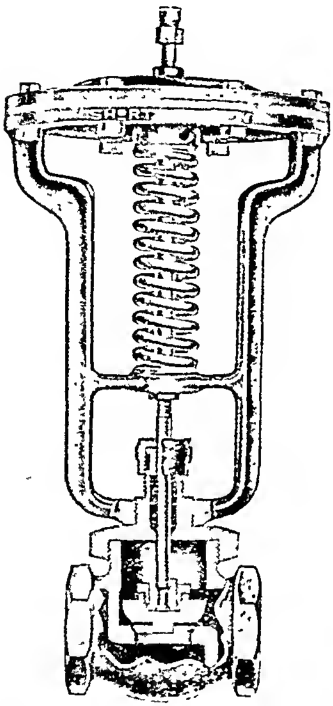


Fig. 113.—Direct-acting, single-seated diaphragm valve

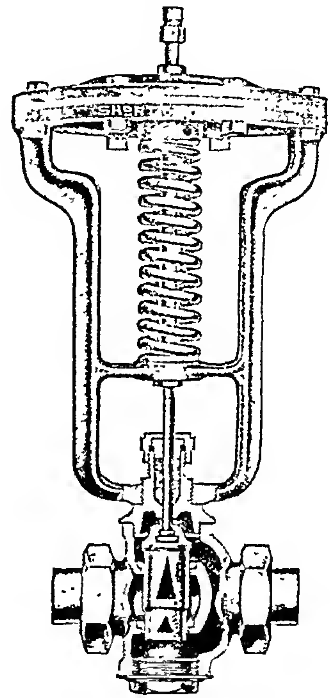


Fig. 114.—Double-seated V-port throttling valve

controlled apparatus is slight or the apparatus itself has a high heat-storing capacity. On the other hand, throttling control is desired where the lag is greater. In general, direct-acting valves are used to control heating media and reverse-acting to control cooling media. The controlling pressure, however, may be used to cause a valve to respond either directly or reversely to a rise in temperature, and hence the choice of valve depends upon whether it is open or shut upon failure of the control pressure. Balanced valves are not usually intended for pressure-tight service.

In some cases a valve has two separate diaphragms When a cycle controller is used to terminate a heating period pressure upon the second diaphragm shuts off the heating medium independently of the temperature control system

The Drayton Regulator and Instrument Company manufacture a packless type of valve operated by heat A metal bellows takes the place of a stripping-box The valve is closed on circuit being established by the expansion of a metal bellows containing a volatile liquid heated by means of a resistance coil The operating bellows and heating elements are enclosed in a casing fixed at the top of the valve The valve opens and closes slowly (within about 2½ to 4 minutes) so that hammer action caused by snap-action valves is avoided The valve can be used only in low pressure systems of about 5 lbs per square inch For higher pressures a balanced valve with stripping box must be used

Three-way valve

The Sarco three way valve illustrates another form of valve designed for particular purposes (See Fig 115)

For instance in diesel engines suitable control of the cooling water is vitally important to minimize wear and distortion and to promote efficiency The three way valve actuated by a liquid expansion thermostat in the oil supply causes the water either to circulate back round the engine or be diverted to a cooler before returning to the engine

With marine engines the danger of the thermostat failing so causing the water to be fully recirculated without cooling is guarded against by a fusible device This consists of a spring held in compression by low temperature solder A small quantity of the circulating water flows around this spring chamber and, should the water become overheated will melt the solder release the spring and cause the piston valve to be forced to the position where the water is diverted to the cooling system

Pilot operated steam valve

An interesting example of a pilot operated on off piston valve used to control the steam supply to storage vessels such as calorifiers and process tanks is the Sarco type *P* (See Fig 116)

Steam is admitted through a port *E* to a chamber *F* and thence via a pilot valve *G* to the underside of a piston *C* Pressure is built up under the piston until it overcomes the resistance of the spring *D* and the rod *B* opens the main steam valve *A*

When the controlled temperature is reached the thermostat which may be of the liquid filled or other suitable type causes the valve closing element push

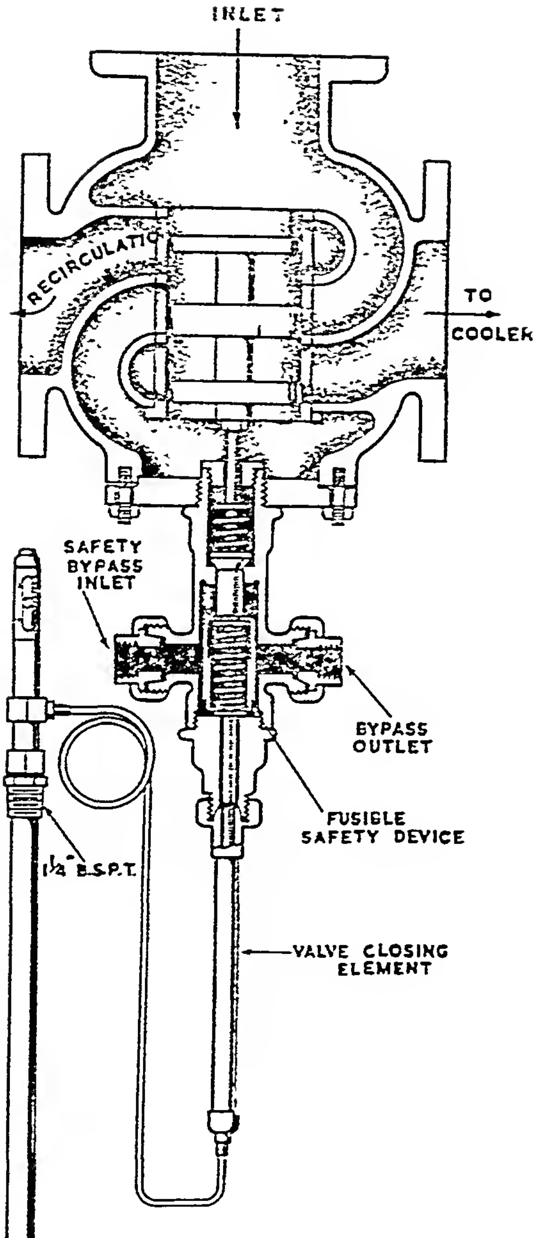


Fig. 115.—Sarco three-way valve

rod H to close the pilot valve G cutting off steam to the underside of the piston. The steam trapped underneath the piston leaks away between the piston wall and the cylinder, allowing the spring D to close the valve A.

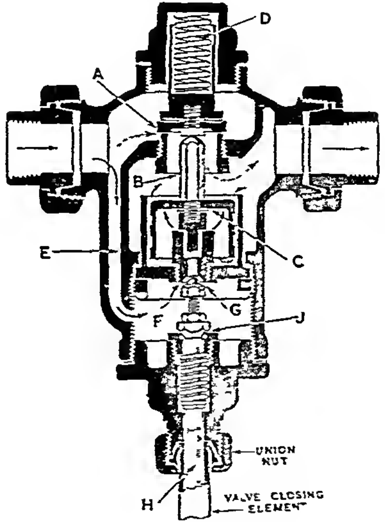


Fig. 116.—Pilot-operated piston valve

Sarco Type D

Cone nut J forms a seal so that when the thermostat element is removed under steam there is no undue leakage to atmosphere.

Unsystematic response of valves

Unsystematic response of flow of the heating-supply medium to the thermostat action, particularly detrimental to proportional control, may result from valve errors such as leakage in the control valve or in the by-pass ; inaccurate valve position, from friction or from unbalanced valves on fluctuating pressures ; and non-proportionality, from the cutting of the valve seat, a greatly oversize valve operating at low lift, a non-proportional or globe valve, flashing in the valve ports, or from limitation of flow by inadequate piping. In the more precise throttling-control installations, where valve changes must be accurate and minute, valve positioners have come into use to eliminate errors of valve friction and unbalance. In every control installation, the control valve must be sized to be the " bottle-neck " of the control-fluid system.

To meet one of the most frequent difficulties encountered in valve design, that of producing a tight yet low-friction gland for the valve stem, a bellows type has been developed. The bellows is sealed at one end to the valve plug and at the other to the valve body.

Failure of control

In specifying a control valve it is usual to state what the valve should do on failure of the electricity or the air supply to the controller. The most usual conditions are that the valve should either close or open fully, but cases do arise, where it is better that the valve should remain locked in the position it occupies at the time of failure. Similarly, means are sometimes provided for emergency operation of the valve, either manually or from an auxiliary power supply.

Valve characteristics in automatic control

For application in proportional control systems, valves of the sliding stem type are available with a variety of inner valves which provide markedly different curves of flow vs. stem position (lift). Also rotary stem or butterfly valves by their inherent design yield variously shaped curves of flows vs. vane position. Such a curve is termed the " valve characteristic." The importance of the valve characteristic is determined by specific properties of the process and control system in which the control valve is to be used. The characteristic may, or may not, have an effect on closeness of control. The importance of valve characteristics in this respect has been ably discussed by Ross[7].

With a constant pressure differential across a proportional control valve it is possible to obtain test curves relating flow against lift obtained under this imposed condition. Such a curve is known as the "inherent valve characteristic." When the valve is installed under actual conditions, where the pressure differential may not be constant, the curve is modified and provides what is termed the " effective valve characteristic."

Variations of pressure differential may be due to variations in fluid pressure (*a*) at the source of flow or (*b*) at the end of flow and (*c*) at the source and end at the same time and (*d*) through the length of the piping to and from the valve

For instance pressure of fuel gas to burners, or steam to heating coils, may vary upstream from the control valve and cause an indefinite fluctuation in the pressure differential across the valve Wide variations in this pressure should be controlled by a pressure regulator for the ultimate in automatic control Friction in the pipe and the presence of hand valves and fittings in the valve piping circuit will cause a variable pressure drop which more or less alters the pressure differential across the control valve.

If therefore the valve is sized with the effect of friction losses neglected, it is possible that even the normal rate of flow required by the process which might be 60 or 70 per cent of the maximum could not be obtained

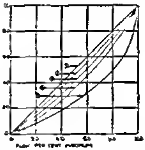


Fig 117 —Pressure losses in lines and fittings

Their effect on an inherently linear valve characteristic

	(1)	(2)	(3)	(4)	(5)
Pressure drop in line %	0	20	40	60	80

Neglect of the friction losses in the valve piping circuit thus decreases the rangeability of the control valve—that is the ratio of maximum to minimum flow obtainable

Even though the valve may be sized with the effects of friction losses taken into account the fact that these losses decrease from a maximum at capacity flow to a negligible amount at low rates of flow causes the inherent characteristic to be altered

With a valve having a linear inherent flow lift characteristic if the percentage of the total differential absorbed in the lines and fittings at maximum flow is increased the curves relating flow to valve lift become increasingly concave in shape as the pressure drop in the lines increases Fig 117 The flow for a given intermediate lift becomes increasingly greater because the pressure loss in the lines has decreased from that at a maximum lift by an amount proportional to the square of the velocity of flow, more pressure differential is thereby left across the valve to produce flow However, if the friction loss

does not exceed about 40 per cent of the total available pressure differential in the line, the inherent flow lift characteristic is not altered too seriously.

Control requirements of processes

In a process using an automatic controller and requiring a fixed average quantity of heat supply to maintain the desired temperature and also a fixed set point, it is well known that there is one adjustment of the proportional band (throttling range) termed the " optimum band," which provides closest control[7]. Basically, this means that the process requires a certain change in flow of control agent with unit change in the temperature to endeavour to maintain the temperature at the set point. This relation is sometimes referred to as the corrective action rate of the automatic controller. This function required by the process involves the valve capacity as well as the proportional band and scale range of the control instrument, such that

$$\text{corrective action rate} = \frac{\text{valve capacity}}{\text{proportional band} \times \text{scale range}}$$

This expression is based on the assumption that the valve characteristic and scale calibration are linear.

For example, a controller with a 0° to 200° F scale is found to have an optimum band setting of 20 per cent when operating a valve with a linear characteristic and a capacity of 100 gallons per minute. Then,

$$\text{corrective action rate} = \frac{100}{0{\cdot}2 \times 200} \text{ or } 2{\cdot}5 \text{ g.p.m./° F}$$

With other conditions remaining constant, the above expression indicates that, if for example, the scale range is increased the proportional band should be accordingly narrowed so that the corrective action rate remains unchanged. Similarly, if the valve capacity is increased, the band must be widened to maintain the same rate.

Changes in process load or set point, however, may or may not require a new corrective action rate, depending upon the nature of the process.

An important characteristic pertinent to the consideration of all processes is " capacitance," which is the change in quantity of energy or material stored per unit change in some reference variable. Many temperature control applications, such as are found with simple kettles, vats or pots, have only one appreciable capacitance, and require a constant corrective rate at all loads.

On the other hand, temperature processes of the heat exchanger type have more than one significant capacitance (usually two, but sometimes three or more) and involve more complex factors such that the corrective action rate should change considerably at different loads in order to maintain optimum control. Such changes are difficult to predict and vary with the relative values

of the capacitances and lags in the particular system In general, however, with such multiple capacity processes having substantially constant capacitances the corrective action rate should decrease with decrease in process load Non-linear functions, such as the effect of radiation losses at high temperatures as compared with that at lower temperatures, further complicate an exact analysis of such processes and tests are necessary to determine the required corrective action rate under varying loads

The corrective action rate is of importance under some, but not all operating conditions For instance in processes involving small lags compared to their capacities the proportional band required tends to be narrow In such cases, for a relatively small change in pen position the controller provides considerable change in the controlled air pressure to the valve This action results in an equally large change in the valve lift With a 10 per cent band, for example, a 2 per cent change in pen position will result in a 20 per cent change in the valve lift, so that the effect of any particular valve characteristic is lost—the valve action approaches two-position operation.

It may be concluded, therefore, that where the proportional band is 10 per cent or less, no specific flow lift charactertstic is required, regardless of the process, or changes in load and set point

Again in certain processes only momentary changes in load exist For such applications a proportional controller is sometimes used, but with a constant set point no particular valve lift-flow relationship of the valve is required Choice of the inner valve is based upon its physical advantages only, such as resistance to erosion due to wire-drawing

The valve-lift-flow relationship becomes of importance in a heat exchanger type of process where a decrease in the corrective action rate with decrease in load is required A proportional controller with automatic re-set (floating action) is generally used in this type of application The valve should provide gradually smaller changes in flow for unit changes in lift toward the lower values of flow in order to maintain optimum control under all loads The slope of the valve characteristic would be greatest at the lowest flow and gradually flatten out towards the maximum flow The characteristic of valve 2 in Fig 118 is of the general shape required For example, an increase in lift from 20 to 40 per cent changes the flow by only about 3 g p m , whereas the same increase in lift from 60 to 80 per cent changes the flow by about 10 g p m

It must be emphasized, however, that the exact shape of the curve for such processes, where the corrective action rate should change, depends upon the required values of the rate at the different loads The change in these values with load will vary with the individual process

In applications where the set point is shifted frequently but the load remains substantially constant, requirements of the valve characteristic vary widely depending upon the particular combination of the following factors (*a*) normal

flow rate of the control agent at the new set point, (*b*) whether the corrective action rate should remain constant, and (*c*) linearity of the controller scale.

Shift of the set point in most applications necessitates a new normal flow, even though the load remains constant.

In these processes with no load changes a proportional controller without automatic reset is generally used. When the set point is shifted, the manual re-set must therefore be readjusted to provide a new normal flow. Proper selection of the valve characteristic cannot then eliminate controller adjustments but may obviate altering the proportional band setting and thereby simplify the adjustments. For example if the corrective action rate should remain unchanged at the new set point and a linear scale is used, a linear valve characteristic will maintain the desired control action.

In most industrial furnaces, however, the corrective action rate changes as the set point shifts: the flue temperature rises at higher flows for increased

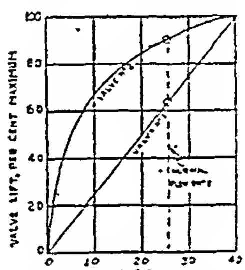


Fig. 118.—Two different valve characteristics
Their effect on lift flow relationship

set points and results in lower combustion efficiencies (less heat transfer) for a given amount of fuel input. This effect, combined with the nonlinear action of radiation losses from the furnace walls, requires an increase in the corrective action rate at higher set points or valve flow-lift curve somewhat similar to that shown for valve 2 in Fig. 118 if optimum control is to be maintained without change in the proportional band setting.

Thermocouples provide an essentially linear scale, but vapour-pressure thermometers and radiation pyrometers exhibit scales which widen towards the high end in approximately an inverse logarithmic manner. Inasmuch as the proportional band action of the controller functions to change the valve position on a linear basis with respect to pen movements, when set point changes are made, this scale characteristic alters the change of valve lift with unit changes in the controlled temperature. In the selection of the optimum valve characteristic for this purpose, therefore, this effective widening of the proportional band as the set point is moved downscale must be considered in

conjunction with the required corrective action rate If the required corrective rate remains unchanged when the set point is lowered, the valve characteristic should provide a slightly greater increase in flow per unit change in lift at the lower flow rate in order to compensate for the effective widening of the proportional band

On the other hand, if the required corrective action rate should decrease at the lower set points the non linear scale characteristic alone may compensate for the necessary decrease by the widening of the proportional band In such a case, a linear valve characteristic would be chosen

Where set point changes are made at infrequent intervals it may be preferable to rely on controller adjustments than to require special valve characteristics

Where possible complete flow data and allied process conditions are desirable in choosing a control valve but if not available such effects can only be approximated by empirical formulae After the valve is in operation pressure readings can be obtained from suitably chosen tapped points for given positions of valve lift By this means improperly selected control valves can be diagnosed and remedies applied

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CHAPTER 19

Classification of heat-exchangers

TEMPERATURE-CONTROL is fundamentally the regulation of heat-exchange. There are, of course, many ways of exchanging heat, and the type of control employed will be governed to a large extent by the system used. A general survey of the various forms of heat-exchangers will, therefore, not be out of place.

Heat-exchanger design depends on a number of factors, amongst the more important being the quantities of the media involved, temperatures, heat requirements, heat-storage capacities, and the amount of heat-transfer surface and its effectiveness. This effectiveness depends on many factors, but most important, perhaps, are the film coefficients, which are in turn dependent on the media, their temperatures and velocities.

Haigler[1] has classified the various forms of heat-exchangers and represented them diagrammatically. Most of the forms can be represented by two contiguous rectangles, representing supply and demand sides, the length of the common wall signifying the amount of heat-transfer surface, and the thickness indicating the thermal resistance. The width of each rectangular area signifies the thermal capacity per unit of heat-transfer surface, so that each area indicates the total thermal capacity on that side.

The sensitive element of a temperature-controller is indicated by S, while the valve V regulates the supply of heating fluid.

In continuous processes the heat supply and demand are, on the average, equal. The effect of the thermal capacity on momentary fluctuations is determined by the amounts of stored heat absorbed or released during a temperature-fluctuation in comparison with the steady-state heat quantity. Obviously, if the storage heats (products of thermal capacities by temperature-fluctuations) are negligible in comparison with the steady-state heat quantity, their effect on control is insignificant. When, however, the storage heat is an appreciable quantity, as is usually the case, the effects of thermal capacity must be carefully considered. In batch processes the heat balance approaches the limiting case where all of the heat requirement is storage heat.

Simple heat-exchangers

Let us now consider some typical simple liquid-liquid heat-exchangers, each with the same demand conditions and same heating surface, but with different thermal capacities and directions of flow. Fig. 119 (a) represents a

simple concentric tube (pipe within a pipe) exchanger connected for counter-current, or opposed flow operation with the small inner pipe on the supply side and the large annular space on the load side The temperature-sensitive element S is placed in the outlet of the exchanger, or in the pipe immediately adjacent thereto In this heat exchanger a temperature-change, as a result of any upset in the balance of heat demand and supply, reaches S in a minimum time Consequently, with on and-off control, the heat input pulses are of

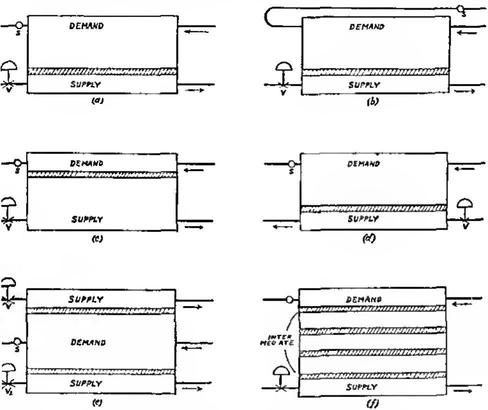

Fig 119 —Some forms of heat exchangers

short duration and correspondingly small in amplitude The small quantity of heat available from the low capacity on the supply side of the heat exchanger, as the control valve shuts at the end of a cycle, is able to raise the temperature of the high capacity on the demand side only a slight amount before it declines again under the influence of new material flowing into the demand side of the heat exchanger Obviously, at higher loads the oversboot is reduced and the decline in temperature follows more quickly, with corresponding improvement in accuracy of control Conversely, at lower loads the cycles are worse Thus

we see why a very much underloaded heat-exchanger on open-and-shut control may cycle badly, while when adequately loaded it controls very closely.

Similarly, with proportional control the heat exchanger shown in Fig. 119 (*a*) controls accurately. The heat-exchanger can follow rapid control changes without hunting. The favourable capacity attenuates temperature fluctuations, thus tending toward stability. As before, at light loads the effect of fluctuations is magnified, thus tending toward instability. For this reason a very much underloaded heat-exchanger on proportional control may also break into a cycle.

Fig. 119 (*b*) represents an exchanger exactly similar to that shown in Fig. 119 (*a*) except that the sensitive element is moved some distance away from the heat-exchanger. The time for a temperature-change to reach position S' is much greater than that taken to reach S. With on-and-off control, the on-and-off periods are correspondingly lengthened and the resulting cycle amplitude is greatly enlarged. With proportional control, the control-band must be much wider than before to make the belated valve-corrections less violent and to allow a wider range for deviations before the limits of proportionality are reached. Thus, with either type of control, a large " transportation lag " entails poorer control.

It is also interesting to note that poor heat transfer in the heat-exchanger, or slow response of the thermal system, has an effect somewhat similar to transportation lag, which may be called "transfer lag." Insufficient or dirty heat-exchange surface and poor film coefficients from inadequate velocities result in high resistance to heat transfer, correspondingly high thermal potentials between the sides of the exchanger, and ensuing control difficulties. Similarly, short and thick or heavy bulbs in air or other poorly conducting media, and restricted circulation past the element can produce a large transfer lag to the thermal element and delay its response surprisingly. This is serious, since the thermal-element response should always be rapid in comparison with the process it is controlling.

Transportation lag and transfer lag together comprise the " response lag " of the system. Response lag, meaning the interval between initiation of a temperature-change and the initiation of a corrective response, must be kept small for best control. Transfer lag is reduced by increased thermal potential ; whence, in cases of extreme transfer lag, normally unfavourable capacity-ratios may control better, since the thermal potential available for control has not been attenuated. Transportation lag is unaffected by thermal potential, being reduced only by reduction of the time interval, as by re-location of the thermal element, by reduction in preceding volume, or by increase in flow velocity.

Fig. 119 (*c*) represents another exchanger similar to that shown in Fig. 119 (*a*) but with the load and supply sides interchanged. The small central pipe is now the demand side, while the large jacket space is the supply side. The ratio of thermal capacities of the demand and supply sides of the exchanger has been

greatly altered With on-and-off control, the cycles are very large The heat available from the large capacity on the supply side of the exchanger after the control valve closes causes a temperature overswing in the small capacity of the load side many times that which results in the case represented by Fig 119 (*a*) A large capacity on the load side is favourable, diminishing, and smoothing out the variations, on the supply side it is unfavourable, amplifying the variations With proportional control the situation is likewise unfavourable, wide-band control being required for stability.

Heat-storage effects depend not only on thermal capacity temperature levels are also significant When the temperature-difference is large, the quantity of heat potentially transferable is large, and difficulties are accentuated With on-and-off control, cycle amplitude is large, with proportional control, cycling can be avoided only by wide-band control with the attendant disadvantages A small temperature-difference is conducive to good control, and sometimes, when little else is possible, merely reducing temperature-difference will improve controllability greatly In milk pasteurizers, for example, the milk is heated not by steam directly, but by circulated water heated to a controlled temperature only slightly higher than the setting of the milk temperature-controller Large transfer lag is always to be avoided because it requires large temperature-differences or thermal potentials which can produce large overswings

Fig 119 (*d*) represents the co-current, or parallel flow type Except for the direction of supply-medium flow, it is similar to the case represented by Fig 119 (*a*), but this single difference is quite significant Not only is the transportation lag obviously increased over its value in the former case, but also the transfer lag is greater In a co-current heat exchanger, the media approach the same outlet temperatures A co-current exchanger is a "temperature leveller," and the average temperature-difference is large In a counter-current unit, the supply medium discharges near the demand-medium inlet temperature, and the demand medium discharges near the supply-medium inlet temperature A counter-current exchanger is a "temperature-exchanger," and the average temperature-difference is small Like counter-current heat exchange, co-current is also adversely affected by unfavourable thermal capacity

Mixed-current heat-exchangers

Many heat-exchangers are neither counter-current nor co-current, but a mixture of the two types Usually, the transportation lag is excessive and the transfer lag greater than need be, with poor controllability the result Mixed-current heat-exchangers may be classed with co-current as difficult to control in the bent-tube types they may be even worse than co-current, because fluctuations in supply or demand may cause local temperature-deviations

simultaneously in the several passes. Successive responses of the thermal element to these deviations tend toward further upsets.

The simple heat-exchangers represent most of the common temperature-control problems. Less numerous, but important in many processes, are the many variations of the compound heat-exchanger types.

Compound heat-exchangers

A typical multiple exchanger is represented by Fig. 119 (*e*). Two supply sections operate simultaneously and independently on the demand section. Similarly, multiple-demand sections are possible. In multiple exchangers, the supply or demand sections, no matter how many, act in multiple and their effects are additive.

Compound heat-exchangers may also be arranged with several sections in tandem or series, as shown in Fig. 119 (*f*). Here the intermediate section or sections introduce additional thermal capacity and additional transportation and transfer lags. Heat must be transferred to, traverse, and be transferred from the intermediate section or sections. Sluggish response is the normal characteristic of a series exchanger, and wide-band control is required. Fractionating columns are typical tandem heat-exchangers.

Very complex heat-exchanger systems are often encountered, particularly in processes where the several steps are interconnected by heat-recovery exchangers. These complex systems can be resolved into combinations of the simple and compound types previously discussed.

Favourable factors for controllability

It follows from the above that the factors favourable to precise control, as reflected in smaller cycles with on-and-off control and in narrower control-bands with proportional control, are—

(1) Minimum transportation lag ;
(2) Minimum transfer lag ;
(3) Minimum temperature-difference ;
(4) Minimum supply-side thermal capacity ;
(5) Maximum demand-side thermal capacity.

The converses are unfavourable, and are to be avoided in good design and operation since, with simple control, they result either in large cycles or in wide control-bands and consequent wandering.

Effect of various heat-exchange media

Examples of liquid-liquid heat-exchangers have been discussed, but the cases of liquid-solid, gas-solid, gas-liquid, and gas-gas heat-exchangers must be considered also. When a solid is substituted for a liquid on one side of an exchanger system, the thermal-capacity ratio may not be greatly changed, as

ordinarily the higher specific gravity of the solid is offset by a lower specific heat

The problems with a solid are more likely to involve homogeneity and accurate sensing of temperature than transportation and transfer lags When the supply medium is a hot gas, such as air, instead of a hot liquid, such as water, the temperature-difference may be considerably greater, yet result in a lower thermal capacity on the supply side with a net favourable effect on controllability Conversely, when the substitution of a gaseous medium is on the demand side, controllability is unfavourably affected With a vapour such as steam, the latent heat offsets in part the effect of the smaller mass

In a plain pipe air heater, the heater mass is so large compared with that of the air being heated that the system is always that represented by Fig 119 (*c*) Therefore, proportional wide-band control is used When, in addition a sluggish thermal element is used, the results will be extremely bad The control-band will be so wide that reset is imperative On the other hand, in a finned-tube heater of equivalent rating the heater mass is much smaller, and the system may approximate that shown in Fig 119 (*a*) Then, provided that the controller—thermal element, control mechanism, and valve—is extremely responsive, on-and-off or narrow-band control can be used When the controller is not sufficiently responsive, the system is the less favourable one shown in Fig 119 (*b*), requiring wide band control with its attendant problems To avoid needless handicaps, it is essential that controller response be more rapid than process response Nowhere is this better illustrated than in air heaters

Classification of special types

Care should be exercised in classifying units which at first appear complicated, in that by analysis they may be placed in a simpler or other category For instance, in a conveyor-drier or tempering furnace, the circulating air or products of combustion, respectively, are controlled in temperature by regulation of the heating medium supplied to coils, or by the regulation of combustion The thermal capacity on the supply side is very large compared with the capacity of the circulating medium, which suggests "wide-band control" The resulting temperature of the load, however, is the significant operating temperature, the load usually having a considerable thermal capacity, sometimes exceeding the thermal capacity of the supply side This, therefore, is of the tandem heat-exchanger type similar to that shown in Fig 119 (*f*), and if the ratio of demand-side heat storage to supply side heat storage is high, the system can be operated by on-and off control The load temperature is controlled precisely by controlling roughly an intermediate transfer temperature

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Theoretical considerations of temperature-control

As indicated in the preface to this edition, there have been, in recent years, many attempts to evolve an analytical theory of temperature-control. None, however, appears to be completely satisfying as yet. While the theoretical foundations are old and the fundamental principles can be found in classical texts on the sciences, analytical methods have not yet penetrated properly into the field of temperature-control.

Most of the mathematical analyses are based on analogies with existing principles of Physics or Mechanics. The most frequent method of treatment of the subject is to consider control processes in general and to refer to temperature-control as an individual member of these processes. German theorists[1] have attempted to correlate the theory of speed governors in turbines and steam engines with process control, whilst British and American writers draw on hydraulic analogies. The application of hydraulic analogies to heat transfer by convection is fairly satisfactory, but similar analogies for heat transfer by the agencies of conduction and radiation are not so, and these latter are best dealt with in a conventional manner.

The aim of the theorists is to evolve a mathematical equation, or equations, which will express the effects of a number of changes in certain factors on the system.

In some cases the method of attacking the problem is to subject the system to what is termed a "standard disturbance" by moving a valve or other unit by a definite amount, deducing the effects of such a change on the system, and expressing the results in the form of an equation.

It will be readily appreciated that if reactions took place instantaneously, the element of time would not need to be considered, and the relation between the position of the regulating valve and the temperature in heat-control would be a simple and direct one. The temperature would move from one position of equilibrium to another without oscillation. Unfortunately, this ideal condition is not attained, although approximations are possible. The heat capacity of the system enters into the problem, involving time-relations. Reacting causes and effects have to be considered, and attempts are, therefore, made to express all these causes and effects mathematically by differential equations of varying orders. In general, the differential equation is raised about one degree for each such cause and effect. The justifiable assumption is made that the factors involved have a linear relationship, in order that the differential

equation shall be linear and more readily solved It may be interposed here that the most usual equation is of the type which describes vibrating systems, but such an equation is, obviously, of no value until reduced to a specific form and its coefficients evaluated The effectiveness of control can then be specified in terms of time-constants One such general equation is as follows—

$$C_n\frac{d^n\varphi}{dt^n} + C_{n-1}\frac{d^{n-1}\varphi}{dt^{n-1}} \quad \cdot \quad C_2\frac{d^2\varphi}{dt^2} + C_1\frac{d\varphi}{dt} + C_0 = 0,$$

this can be reduced to a simple second order form in the case of temperature-control, as follows—

$$C_2\frac{d^2\varphi}{dt^2} + C_1\frac{d\varphi}{dt} = C_0 = 0,$$

where φ is the fractional deviation of the temperature from its standard value $\frac{(T - T_s)}{T_s}$,

Further reference will be made later to this aspect of the subject It will be convenient to adhere for the moment to processes in general, as has previously been indicated is the custom in dealing with the mathematical aspect of processes of which temperature is one

Referring again to the capacity of a system it may be said in general terms that whenever the absorption of energy occurs there must be a resistance to the flow of energy from this part of the process, otherwise the storage of energy would be impossible, regardless of the amount supplied Thus with each capacity there is always associated at least one "resistance" Process lags occur as a result of combinations of these capacities and resistances Three types or classes of process lags have been recognized,[2] as follows—

(1) *Capacity Lag*—a retardation (not a delay) of the condition of a given process variable, resulting from the ability of the immediate part of the process to absorb and store up energy

(2) *Transfer Lag*—a retardation (not a delay) of the condition of a given process variable, following an instantaneous change in some related variable, itself resulting from resistance offered to the flow of energy between two or more reasonably isolated capacities of the process

(3) *Distance-velocity Lag*—a direct delay or postponement of the beginning of a change in a given process variable, following an instantaneous change in a related variable at some other point in the process, itself resulting from any characteristic of the mechanical embodiment of the process which requires time to conduct the effect of the change to a process whence it may affect the given variable

A process possessing "Transfer Lag" must consist of at least two capacities "Distance-velocity Lag" is the only type of lag expressible in time units,

"Capacity Lag" and "Transfer Lag" come under the heading of functional time-lags. "Distance-velocity Lag" may be termed finite time-lag.

Most German authorities on regulation use dimensionless quantities. Changes which take place are represented by their ratios as compared with some fixed values, either the average or the maximum, rather than their actual values. The final equations are then expressed in terms of ratios (dimensionless quantities) and time. By this means the form and use of the mathematical relationships is simplified. The results, however, can readily be converted to absolute quantities when required.

Hydraulic analogy

As previously stated, British and American writers use a diagrammatic representation of a process, based on hydraulic principles. Fig. 120 illustrates

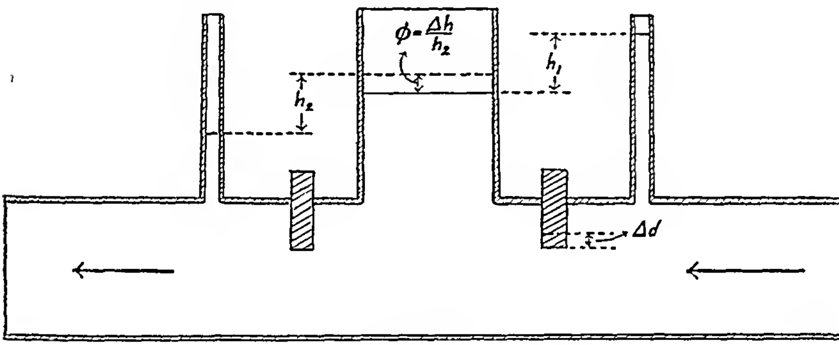

Fig. 120.—Hydraulic analogy of a "single-capacity" process

a simple diagram of this form and refers to a so-called "single-capacity process." By interpretation and extension, this type of diagram can be made to represent various forms of temperature-regulation problems, bearing in mind the limitations previously expressed.

The process is considered to be a series of capacities separated from one another by resistances, so that flow from one capacity to the other is accompanied by a decreased energy level, represented by a difference in liquid levels (Fig. 120). The flow through the resistances may be made proportional to the difference in levels ("differential head"), since the flow of heat is inversely proportional to the resistances in its path. The area of the tank represents the capacity of the system or B.Th.U's per degree. This can be considered as the product of the specific heat of the material being heated times its mass, provided that the range of temperature is such that the specific heat remains constant.

If the supply valve is moved suddenly at time $t = t_0$ by an amount Δd,

the increased input flow would, according to the German system of dimensionless quantities, be $\frac{\Delta Q}{Q}$, where Q is the flow rate at equilibrium valve position. A change in level h_2 results, represented by a change $\frac{\Delta h}{h_2} = \varphi$, where h_1 is the differential across the supply valve, and h_2 = the differential across the discharge valve The rate of change of level, or φ', is directly proportional to the increased input flow or disturbance q, and if q remains constant φ' also remains a constant The ratio of φ' to the corresponding value of q_1 is a characteristic of the system of regulation and has been called by Neumann[3] the "sensitivity of the regulating space" The reciprocal of this ratio, or $\frac{q_1}{\varphi'}$, has been called *Anlaufzeit* by German writers, a term which has been variously translated as "application lag," "process-time," "starting time" and "reaction time"

The process just considered has been referred to as a "single capacity" process, as previously indicated, multiple-capacity processes are possible The latter may be subdivided into the following groups—

(*a*) Capacities and resistances in series,

(*b*) Capacities and resistances in parallel, and

(*c*) Series parallel combinations

Many multiple capacity systems can however, be approximated by a single-capacity system with sufficient exactness

Mathematical theories of temperature-control

Some of the principal features of specific mathematical theories advanced by various authors may now be considered For a full description of these theories the reader is referred to the original papers on the subject, to which references are given at the end of this chapter

Callender[4] and his collaborators discuss the question of time lag in its relation to control systems in general They consider that variation in the departure of the temperature from the normal or standard value may be due to three causes first, through uncontrolled disturbances such as fluctuations in the ambient temperature, or variations of voltage on the mains from which the current for the heating coils is taken, secondly, through the operation of the control gear, and thirdly, apart from changes due to these causes, a departure of the furnace space temperature from the normal may in itself give rise to a variation of the temperature

A general expression is given connecting these variations as follows—

$$\frac{d\,\theta\,(t)}{dt} = D\,(t) + C\,(t) - m\,\theta\,(t) \qquad (1)$$

where θ (t) is the departure at time t of the temperature from the set value ;

$D(t)$ is the effect of uncontrolled disturbances and is regarded as a given function of t; $C(t)$ is the effect at time t of the operation of the control; and $-m\theta$ is the inherent effect of variation of $\theta(t)$ from its zero value. Thus $D(t)$ is the disturbing function and $C(t)$ the controlling function. The uncontrolled disturbances do not affect the control directly, but through variations of θ, to which they give rise. For a system with time-lag, the function $C(t)$ then depends on the behaviour of θ not at time t, but at a time $t - T$, where T is the time-lag, which is assumed to be constant.

The effect of the control at time $t + T$ is determined by the behaviour of $\theta(t)$ at time t. The dependence of $C(t + T)$ on $\theta(t)$ expresses the behaviour of the control, which may be put into the following form, termed the "law of control"—

$$-C(t+T) = n_1\,\theta(t) + n_2\,\dot{\theta}(t) + n_3\,\ddot{\theta}(t) \qquad (2)$$

where the dots denote differentiation with respect to time, and n_1, n_2, and n_3 are constants. For satisfactory control these constants must lie within certain limits of value. By using different values of these constants, the behaviour of the control from the point of view of sluggishness and damping, etc., can be determined.

In their analysis, Callender and his collaborators assume the time-lag to be unity and write—

$$t/T = \tau,$$

and $\quad mT = \mu, \quad n_1T^2 = \nu_1, \quad n_2T = \nu_2, \quad n_3 = \nu_3$;

ν_1, ν_2 and ν_3 being called the "control-constants" of the system.

$TD(t)$ is taken as equal to $\psi(\tau)$,

and $\quad TC(t)$ " " " $c(\tau)$

$\psi(\tau)$ is referred to as the disturbing function. For θ is written $\theta(\tau)$, regarded as a function of τ rather than of t.

From this, equations (1) and (2) become—

$$\frac{d\,\theta(\tau)}{d\tau} = \psi(\tau) + c(\tau) - \mu\,\theta(\tau) \qquad (3)$$

$$-\frac{dc(\tau+1)}{d\tau} = \nu_1\,\theta(\tau) + \nu_2\frac{d\,\theta(\tau)}{d\tau} + \nu_3\frac{d^2\,\theta(\tau)}{d\tau^2} \qquad (4)$$

Three methods of investigation were used to study the equations, as follows—

(i) The determination of the normal "modes" of the equations. The behaviour of $\theta(\tau)$ where $\tau = t/T$, the time-lag T being a unit of time, is exponential or damped-harmonic, and the frequencies of the modes and damping constants are found.

(ii) The use of Heaviside operators. The equations (3) and (4) can be expressed in such a manner as to form a pair of linear difference-

differential equations with constant coefficients These are then treated by the Heaviside operational method

(iii) Numerical investigation of particular cases by arithmetical or graphical methods, or by the use of a differential analyser

To deduce the true ranges of suitable "control constants" a genuine time-lag is assumed, instead of a mere sluggishness of starting, analogous to inertia

The physical significance of the "law of control" can be illustrated by considering the control of temperature by steam-heating, the steam supply being controlled by a valve The setting of the valve determines the controlling function, and from the "law of control" with $n_1 \neq 0$, it follows that not the valve-setting itself, but its time rate of change, depends on the value of the temperature and its derivatives, so that the valve-setting depends not only on the behaviour of the temperature at any particular instant, but on the time-integral of the temperature, and so on its previous history

Diagrammatical representation of this method of control is shown in Fig 121. The valve S governs the supply of steam to a vessel whose temperature-deviation θ from the correct value is indicated by the position of the arm A The value of θ is to be kept as small as possible The value $S(t)$ depends on the setting of the valve S at time t, and the equation expressing the "law of control" becomes

$$-S(t) = n_1\,\theta(t) + n_2\,\theta(t) + n_3\,\theta(t) \tag{5}$$

The valve S should be moved automatically so that $S(t)$ satisfies this equation In Fig 121 let x be the height of the lower end U of a rod hanging from the arm A above its position when $\theta = 0$, and suppose x is proportional to θ Let y be the height of a cylindrical vessel W_2 above some arbitrary level, this height being made proportional to the value of $-S(t)$ by means of a connexion to the valve S through a cam as shown A similar vessel W_1 is placed so that the contact U can touch the surface of the liquid in W_1 The liquid in W_2 passes through a siphon pipe, from an intermediate point Q of which a branch pipe is led to a dish D, of large cross section compared with those of W_1 and W_2, so that changes of level of the liquid in D can be neglected This level is adjusted to be that of U when $\theta = 0$

If the mechanism M, actuated by the contact at U, causes S (and so W_2) to be moved in such a way that the liquid surface in W_1 is kept just in contact with U, then if the cross sections of W_1 and W_2 are C_1 and C_2, and the resistances of the pipes from Q to D, W_1 and W_2 are R, r_1 and r_2 respectively, then it follows from the equations of motion and continuity of the liquid that

$$y = \frac{1}{C_2 R}\left[x + \left\{(R + r_1)\,C_1 + (R + r_2)\,C_2\right\}x + \left\{R\,(r_1 + r_2) + r_1 r_2\right\}C_1\,C_2\,x\right] \tag{6}$$

This equation satisfies the "law of control," being of the same form, since x and y are respectively proportional to $\theta(t)$ and $-S(t)$.

Thus, if contact of the surface of the liquid in W_1 with U is maintained as θ varies, a law of control of the desired form is obtained. This means that the controlling mechanism only acts at any instant in proportion to the amount of deviation from the set temperature.

The curves relating deviation with time will, after a thermal disturbance of the system, show a gradual return to the normal temperature without continued oscillation.

This form of the "control law" may be extended a stage farther.[3] An auxiliary variable $z(t)$, related to $\theta(t)$ by the equation

$$\dot{z}(t) + B_1 z(t) = B_2 \dot{\theta}(t) + B_1 \theta(t) \quad . \quad . \quad (7)$$

can be introduced into the equation.

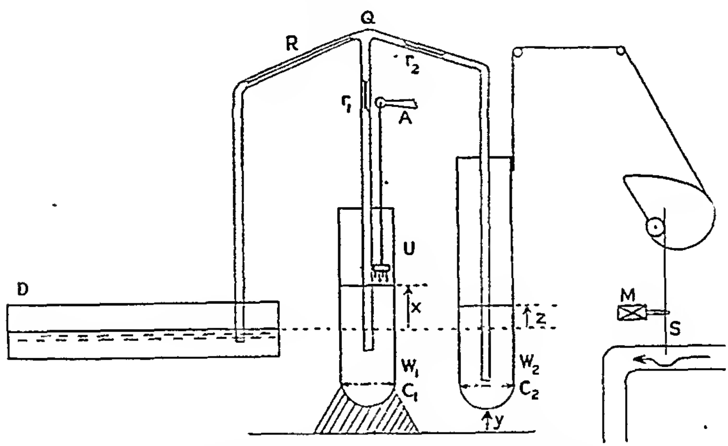

Fig. 121.—Diagrammatic representation of the control law

The law is then expressed in the form

$$-\dot{c}(t+T) = n_1 z(t) + n_2 \dot{z}(t) + n_3 \ddot{z}(t) \quad . \quad . \quad (8)$$

This law reduces to the former control law (2) if $B_2 = 1$ or $B_1 \rightarrow \infty$, B_2 remaining finite ; but in the case under consideration $B_2 > 1$.

To apply this law in practice, the principle of the control can be illustrated diagrammatically as before. In Fig. 122 the displacement $x(t)$ of the indicating arm A indicates the deviation from the set temperature, and so is proportional to $\theta(t)$. The control law (6) will be attained if the same mechanical means of obtaining the relation (2) is used, but the displacement $x(t)$ is now made proportional not to $\theta(t)$ but to $z(t)$, related to $\theta(t)$ as explained above.

Fig 122 shows the principle of an electrical means of attaining conformity to the law

Here U is a movable group of contacts and A is the indicating arm of the thermometer These two components are the same as in Fig 121 In Fig 121, however, U was suspended directly from A, so that the displacement x of U was directly proportional to the temperature deviation θ This direct mechanical connection is replaced by a connection through the electrical circuit shown, A moving a contact over a potentiometer and U being suspended from the indicating arm of a voltmeter V which measures the potential at the point P of the circuit (in practice a thermionic voltmeter is usually employed)

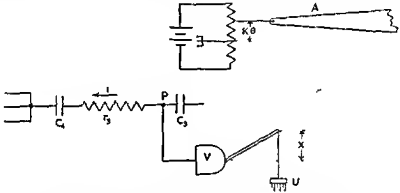

Fig 122—Electrical representation of the control law

If $K\theta$ is the potential tapped off on the potentiometer, V_p the potential at P, and i the current in the direction indicated in the diagram, we have

$$\left(\frac{1}{C_3}+\frac{1}{C_4}\right)\int i\,dt + r_3 i = K\,\theta,$$

and

$$\left(\frac{1}{C_4}\right)\int i\,dt + r_3 i = V_p\,,$$

whence, eliminating i,

$$\frac{dV_p}{dt}+\left(\frac{1}{r_3}\right)\left(\frac{1}{C_3}+\frac{1}{C_4}\right)V_p = K\left[\frac{d\theta}{dt}+\left(\frac{1}{r_3\,C_4}\right)\,\theta\right] \qquad (9)$$

so that the voltmeter deflection x, which is proportional to V_p, satisfies a relation of the form 8 The values of B_1 and B_2 in 2 can be adjusted by choice of scales and of r_3, C_3, C_4

The remainder of the control apparatus, namely that portion of it which gives the relation 2 between z and the controlling function C, is the same as that of Fig 121, with the simplification that the vessel W_1 could be moved directly from S, and W_2 omitted A mechanical, hydraulic, or electrical method

can be used to obtain the relation 2, independently of the type of method used to obtain the relation 7.

Turner,[6] in order to determine the mathematical relationship between the sensitive element and the heating element, designed a special form of experimental oven. It consists of a metal cylinder of length l_1 and cross-sectional area A. The "slave" coil, as he terms it, or heating element, and the "master coil" or sensitive element encircle this cylinder; the slave coil at the bottom being separated from the master coil by a distance l up the cylinder. The heating power P_1 in the slave coil is controlled by the temperature θ of the master coil. The rate of change of power input with temperature, or control sensitivity, is a known variable. When the control sensitivity is made large, thermal oscillation takes place, due to the slave and master coils mutually affecting each other thermally. Analysis shows that if $l = l_1$, or $> 0{\cdot}55 l_1$, thermal oscillation arises when the control sensitivity per unit area of cross-section, $-\frac{1}{A} \cdot \frac{DP_1}{d\theta}$, is increased beyond a critical value S, where $S = 17{\cdot}6\ K/l$, or $35K/l$, respectively. In both cases the period of oscillation is

$$T = \frac{0{\cdot}57\ l^2 \rho c}{K},$$

where K is the thermal conductivity of the material of the cylinder, ρ its intensity, and c its specific heat.

As indicated above, Turner analyses the condition where S is just equal to $-\frac{1}{A} \cdot \frac{dP_1}{d\theta}$, and does not consider the case where S is much less than that value. In the latter case it is anticipated that the curves relating the thermal changes with time would be different in character from, and sharper than, those obtained when S is equal to the value.

Turner does not devote much attention to the amplitude of oscillation, but considers mainly the frequency of oscillation. From experiments with his special oven he concludes that large oscillation frequency and small oscillation amplitude go together.

Where the master and slave coils are intermingled regularly, as in certain forms of thermostat furnaces, conditions defined by the equation $S = 35K/l$ (which applies in this case) produce the greatest control sensitivity. Turner states that to effect this and avoid self-oscillation altogether, or, if oscillation cannot be avoided, to make T as small as possible, the master and slave coils should be in close juxtaposition and should be wound in good thermal contact with a chamber of high conductivity. $K/\rho c$, which is the diffusivity of the material, should be as large as possible.

The effect of the thickness of the wall of the chamber on penetration by the hunting oscillation is expressed by the ratio between the amplitudes at

the two surfaces of the wall, which ratio is

$$\frac{l h}{2} \cdot \sqrt{\frac{\omega}{2 \sigma}},$$

where h is the wall thickness, $\omega/2\pi$ is the hunting frequency, and $\sigma = K/\rho c$ the diffusivity of the material.

A thick wall is therefore desirable for two reasons to reduce "hunting," and to reduce temperature-gradients along the walls

Turner considers that hunting is necessarily present if the heat supply is controlled in discrete quantities, and is also present when a continuous relation exists between temperature and heat supply, provided the control sensitivity exceeds a certain critical value That is, stability of control is not necessarily improved merely by increasing the sensitivity of the temperature-sensitivity device (The natural limit to the sensitivity of all measuring processes has been analysed by Barnes and Silverman[7])

It may be said here in brief that the necessary qualities of automatic temperature are stability, reliability, and sensitiveness, in the order named A sensitive control which hunts is of no use, whilst a sensitive and stable control which is not reliable is also of little value

Turner assesses the specific effectiveness of the thermostat by a figure of merit, represented by the ratio between the change in temperature of the furnace enclosure if there were no thermostatic control, and the change of temperature which *does* occur with thermostatic control He assumes that two factors, only, affect the constancy of temperature, viz change of ambient temperature, and electrical power-supply variation Assuming steady conditions, the figure of merit

$$\eta = \frac{N_1 + N_2}{N_1} \simeq \frac{N_2}{N_1},$$

where N_1 is a constant related to the power emitted from the furnace (by conduction, convection, and radiation), $N_1\,(\theta - \varphi)$ is the value of this power when θ is the furnace temperature and φ the ambient temperature, and

$$N_2 = \frac{\delta P_1}{\delta \theta},$$

where P_1 is the heating power in the slave coil (i e controlled by the master coil)

It is deduced that the higher the temperature of the furnace the easier it is to obtain a large figure of merit , and further, that the attainment of a large figure of merit is not dependent on the provision of good thermal insulation between the furnace and its surroundings The advantage accruing from insulating the furnace appears to lie in the reduction of power required to maintain the desired furnace temperature

Ivanoff[8] obtains numerically the frequencies, dampings and amplitudes, etc. of particular cases and deduces a "law of response" to the controlling mechanism. A regularly-repeated disturbance is introduced in order to give a basic periodicity to which Fourier's analysis is applied. Ivanoff introduces the term "potential temperature," defined as "the limiting value of the temperature-change which the plant [meaning temperature-controlled system] tends to attain for a given alteration in the position of the controls"; the "controls" being fuel valves, dampers, etc.

He discusses the oscillations of temperature—potential as well as actual or recorded temperatures—which are produced when the sensitivity of the controller is increased to a point where a periodic oscillation of sinusoidal form occurs. Equations are derived to express the conditions for stability for "on-and-off," proportional, and floating methods of control.

Ivanoff likens time-lag to the action which occurs when heat flows into a semi-infinite solid. If the temperature of a control mechanism at the surface of the solid is made to vary periodically so that

$$\theta = A \sin mt,$$

where A is the amplitude and $\sin mt$ the controlling disturbance, in which

$$m = \frac{2\pi}{\text{period of oscillation}},$$

then the recorded temperature is

$$A e^{-c\sqrt{m}} \sin (mt - \sqrt{cm}),$$

where e is the base of natural logarithms and c a time indicating the amount of lag that is characteristic of the system.

Prinz has shown that there is a similarity between automatic controllers and negative feed-back amplifiers. These systems can be represented by a closed chain of variables in such a manner that two adjacent variables are connected either by a factor of proportionality or a differential operator.

Thus a deviation from the controlled temperature will influence a sequence of variables to a last variable which finally acts on the initial variable—the deviation of the controlled temperature—to force it back to its rated value or as near to it as the control mechanism will permit.

The dependent variable may (*a*) have a back effect on the immediately preceding independent variable, in which case the variables are interacting or (*b*) may not have a back effect, in which case the relationship is unidirectional. For example the temperature of a thermocouple junction and its current are interacting owing to the Peltier effect; but the temperature of a furnace has a unidirectional relation to the current of the thermocouple measuring it. Prinz's theory is confined to relations of the unidirectional type.

Electrical representation of lag systems

The relation between the input variable ξ ("driving function" in mathematical literature) and the output variable X ("response function") is such that X may follow ξ either (i) in the form of a damped oscillation or (ii) X may vary in a direction towards ξ and remain constant whenever $X = \xi$ without "overshooting" In this case the rate of change $\frac{dx}{dt}$ will be positive for $\xi > X$, negative for $\xi < X$ and 0 for $\xi = X$, or the sign of $\frac{dx}{dt}$ will always be the same as the sign of $\xi - X$

In the simplest case of this type, $\frac{dx}{dt}$ is proportional to $\xi - X$

$$\frac{dx}{dt} = \frac{\xi - X}{\tau} \tag{1}$$

where τ is a positive constant with the dimension of time The system is called a simple lag system or delay element It may form part of the process to be controlled or of the controlling mechanism In the first case the process is usually referred to as a 'single capacity process" having "capacity lag", in the second case the method is called proportional control' by Prinz

A simple lag system can be represented by an electrical condenser C charged through a resistance R If the input voltage charging the condenser is ξ the output voltage across the condenser X, then the relation between X and ξ is given by equation (1)

with
$$\tau = RC \tag{2}$$

The hydraulic analogy used by American authors to illustrate a single capacity process corresponds to the circuit in Fig 122 with a load resistance R ('demand side') across the condenser

Equation (1) may be written

$$\tau\left(\frac{dx}{dt}\right) + x = \xi \tag{3}$$

Under the assumption $\xi = 0$ for $t < 0$, $\xi = \text{constant} \neq 0$ for $t > 0$, corresponding to a sudden application of the voltage ξ at time $t = 0$ the solution (3) is

$$x = \xi\left(1 - e^{\frac{-t}{\tau}}\right) \text{for } t > 0,\ x = 0 \text{ for } t < 0 \tag{4}$$

in particular for $\xi = 1$

$$x = 1 - e^{\frac{-t}{\tau}} \text{ for } t > 0,\ x = 0 \text{ for } t > 0 \tag{5}$$

This is the response of the system to the Heaviside unit function $H(t)$:

$$H(t) = 0 \text{ for } t < 0, \; H(t) \text{ for } t > 0 \quad . \quad . \quad (6)$$

In operational calculus the differential operator d/dt is denoted by the symbol p and it can be shown that to a very large extent p can be treated as an ordinary variable. This property affords a simplification of the theory of automatic control.

Applying the above notation to equation (3) we get

$$\tau p x + x = (\tau p + 1)x = \xi \quad . \quad . \quad . \quad (7)$$

$$x = \frac{1}{1 + \tau p} \xi = q \xi \quad . \quad . \quad . \quad . \quad (8)$$

The operator $q = \dfrac{1}{1 + \tau p}$ is called a simple lag operator and plays an important part in the treatment of control problems.

Prinz has also derived an operational equation for the system and considered the conditions for stability, etc.

Further references[9-15] to discussions on the subject of the theoretical foundations of temperature-control are listed below.

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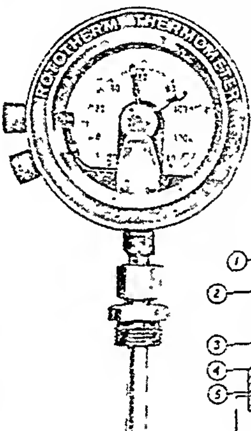
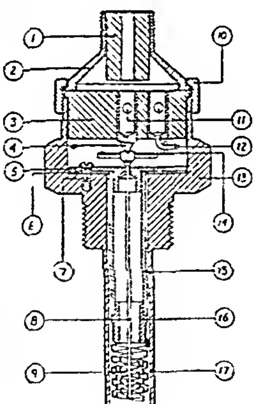
DIAL THERMOMETERS

The British Rototherm Co., Ltd., specialises in the manufacture of bi-metallic, rigid stem, dial type thermometers for all purposes where temperatures between minus 60° F. and 1,000° F. are required. They can be supplied for Co-Axial, Vertical or Flange type mounting and can be fitted with adjustable electrical contacts to operate through relays where temperature control is required.

An interesting instrument is the British Rototherm Co.'s Rotostat (see diagram below) which, while not giving visual indication of temperature, has been designed to provide a useful adjustable thermostat for giving warning when dangerous rises in temperature occur. This warning may be given by the operation of lights or bells when the pre-adjusted setting point on the Rotostat is reached.





1 Rubber Protection Sleeve.
2 Protection Cap.
3 Contact Block.
4 Pivot Contact Pin.
5 Setting Plate.
6 Dial.
7 Setting Screw.
8 System Shaft.
9 Rototherm Bi-metallic Element.
10 Knurled Ring.
11 Fixed Terminal Screw.
12 Fixed Contact.
13 Body of Rotostat.
14 Moving Contact.
15 Inner Stem.
16 Element Holder.
17 Outer Stem.

The British Rototherm Co. also manufacture Distance Reading Thermometers of the Vapour Pressure and Mercury types. If you are interested in temperature indication and control, your enquiries are invited.

Rototherm

DIAL THERMOMETERS

THE BRITISH ROTOTHERM CO. LTD.

Merton Abbey, London, S.W.19. 'Phone LIBerty 3406
and at 87, St. Vincent Street, Glasgow, C.2.